Development and calibration of indicators of the quality of agricultural soils of the South of China

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Mise au point et calibration d'indicateurs de la qualité de sols agricoles du Sud de la Chine

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I

Assessment of soil quality – General Indicator of Soil Quality in plantations in South of China

Résume

Un système d'indicateurs de la qualité des sols a été mis au point pour comparer l'effet des types de gestion des sols dans une région du Sud de la Chine. Ce système synthétise en 5 sous indicateurs et un indicateur général la nature complexe du système sol qui exige la prise en compte simultanée des aspects physique, chimique et biologique. Les méthodes statistiques multivariées sont utilisées ici pour traiter des tableaux de données comportant des dizaines de variables différentes.

On a évalué la qualité du sol dans la région de YingDe, (Province de Canton dans le sud de Chine), sur 20 parcelles avec différents type d'utilisation du sol: plantations de thé à différents degrés d'intensification (labour et fertilisation), plantation d'orangers, de canne à sucre, de bambou et de pin.

Un ensemble de paramètres mesure l'état physique, chimique, la qualité et quantité de matière organique, l'aggrégation et la morphologie du sol superficiel (0 à 5 cm), ainsi que la diversité et la composition de la communauté de macroinvertébrés du sol. Ces 5 sous-indicateurs (physique, chimique, matière organique, morphologique, biodiversité) sont ensuite regroupés pour former un indicateur général de la qualité du sol (IGQS).

Le diagnostic ainsi effectué montre des différences significatives entre la nature des plantations, entre les méthodes de gestion et l'ancienneté des diverses plantations de thé. Les plantations de thé recevant les plus grands apports de résidus organique et de fumier ont des valeurs d' IGQS plus élevées que celles qui reçoivent de l'urée comme apport azoté, La plantation d'orangers fertilisée avec du fumier, de la chaux et et du N, P, K comme fertilisants a la valeur d'IGQS la plus élevée des 20 sites. Comparé aux pratiques recourant à la fertilisation chimiques et à l'utilisation de pesticides chimiques, l'apport de fumiers ou résidus organiques, combiné à la lutte naturelle contre des insects nuisibles améliore beaucoup la qualité du sol ainsi que le recyclage du carbone. Le sous-indicateur de morphologie du sol semble être affecté par le type d'engrais.

La matière organique est le facteur le plus important dans la détermination de la qualité du sol. Des apports importants favorisent la diversité, l'abondance et l'activité des invertébrés ; ceux ci produisent plus d'agrégats biogéniques qui peuvent exercer leurs effets à long terme sur les divers services écosystémiques du sol. Le sous indicateur chimique est apparu très sensible aux applications de fumier, d'engrais chimique ou de chaux. A l'inverse, l'indicateur physique est moins fluctuant, la teneur en argile étant la principale variable qui discrimine les sites sur des critères physiques.

Mots clés : Indicateur général de la qualité du sol ; Analyse de Composantes principales ; macrofaune du sol ; morphologie du sol

Abstract

Soil quality research differs from some soil management research in that it emphasizes the multifaceted nature of soils and requires that physical, chemical, and biological aspects of the soil be considered simultaneously. Unsupervised methods of multivariate statistics are powerful tools for this integrated assessment and can help soil researchers to extract much more information from their data. In our study, soil quality indicator is constructed by divers measured properties by this technique. Soil quality was assessed on a set of 20 plots submitted to different types of land use, tea plantations with diverse degrees of intensification and fertilizer, orange tree plantation, sugarcane, bamboo forest, pine forest and wasteland in the region of Yingde (Guangdong Province, South China). Our study aimed to design a synthetic indicator that allowed quantifying the physical state, chemical fertility, quality and stocks of organic matter, aggregation and morphology in the surface soil (0 - 5 cm) and diversity and composition of soil macroinvertebrate communities. These 5 sub-indicators (physical, chemical, organic matter, morphological and biodiversity) then are combined into a general index. Significant differences were observed among different plantations and tea plantations with different history and managements by general indicator of soil quality (GISQ). Tea plantations that were replanted and with less residue had lower GISQ than plots that had not been replanted, more residue and manure was applied. Tea plantations with urea had lower GISQ than plots applied manure. Orange plantation with fertilizers of manure, lime and N, P, K had the maximum GISQ. Compared with mineral fertilizers or pesticides, use manures or organic residues could improve soil quality, control pests naturally, improve soil C circulation. Soil morphology sub-indicator seems to be affected greatly by the type of fertilizers applied.

Soil organic matter status is observed to be the crucial factor that determines soil quality, which favors the presence of invertebrate, improves it’s abundance and biodiversity; this results in more biogenic aggregates that are created by invertebrate. Chemical sub-indicator is very sensitive to manure, fertilizer and lime

application. On the contrary, physical sub-indicator is less dependent on differences of fertilizer application, it is the clay content that most differs the sites.

Keyword: General indicator of soil quality; Principle component analysis; Soil macrofauna; Soil morphology

I.1 General Introduction

I.1.1 The concept of soil quality (SQ)

Soil is a critically important component of the earth's biosphere, which supports the production of food, fiber and participate in the provision of a wide range of ecosystem services (Glanz, 1995; MEA, 2005). Thus, the thin layer of soil covering the surface of the earth supports most land-based life (Doran *et al*., 1996). However, inventories of soil productive capacity indicate human-induced degradation on nearly 40% of the world's agricultural land as a result of soil erosion, atmospheric pollution, extensive soil cultivation, over-grazing, land clearing, salinization, and desertification (Oldeman, 1994, MEA, 2005). Indeed, degradation and loss of productive agricultural land is one of our most pressing ecological concerns, rivaled only by other human caused environmental problems like global climate change, depletion of the protective ozone layer, and serious declines in biodiversity (Lal, 1998).

Soil quality is essential in sustaining the global biosphere and developing sustainable agricultural practices. Soils are being degraded worldwide through processes of erosion, anaerobiosis, salinization, compaction and hard-setting, organic matter depletion, and nutrient imbalance. Most of these processes are themselves linked to depletion in the diversity and activity of the many species of invertebrates and microbes that operate the different soil functions (Lavelle *et al*., 2006). Central to sustainable agroecosystems must be the protection and enhancement of soil quality. Soil quality is a measurement of their ability to produce plant biomass, maintain animal health and production, recycle nutrients, store carbon, partition rainfall, buffer anthropogenic acidity, recycle added animal and human wastes.

The concept of soil resource management (separate from crop or forest management) for sustaining the productivity of plant systems is critical to ensure the reality of sustainable agriculture and environmental protection. Measuring soil

quality, if properly characterized, should serve as an indicator of the capacity of soils to produce safe and nutritious food, enhance human and animal health, and overcome degradative processes (Papendick and Parr, 1992). Therefore, the overall purpose of this renewed emphasis on soil quality is to develop a more sensitive and dynamic way to document soil conditions, how they respond to management, and their resilience to stresses imposed by land use practices.

The Soil Science Society of America (1997) defined soil quality as, "The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Another organization has suggested that, "sustainable agriculture should involve the successful management of resources to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources" (Technical Advisory Committee to the CGIAR, 1988).

I.1.2 Soil quality indicators

The interaction of soil health along with soil stability and soil resilience contributes to the sustainable use of the soil resource (Lal, 1993). Soil health or quality evaluation should be based upon soil functions and indicators that measure these attributes and their interactions. Soil functions would be defined in terms of physical, chemical, and biological properties and processes and measured against some definable standard to determine whether a soil is being improved or degraded (Karlen *et al*., 1997) by any practice. In turn these attributes describe the soil capacity to perform ecosystem functions such as incorporating, holding and releasing water or energy.

An adequate approach to defining soil quality indicators must be holistic not reductionistic and indicators should thus describe the major ecological processes in soil (Doran and Safley, 1997; Velasquez, in press). Indicators of soil quality should be responsive to management practices, integrate ecosystem processes, and be components of existing, accessible data bases. These indicators must be quantified

to document the improvement, maintenance or degradation of soil quality (Larson and Pierce, 1994). National and international programs for monitoring soil quality presently include a few general biological indicators such as biomass and respiration measurements, nitrogen mineralization, microbial diversity and functional groups of soil fauna (Bloem *et al*., 2003).

An indicator of soil quality is a measurable surrogate of a soil attribute that determines how well a soil functions (Burger and Kelting, 1999). Since soils vary naturally in their capacity to fulfill different functions, quality indicators are expected to be relatively specific to each kind of soil. This concept encompasses two distinct although interconnected components, the inherent and dynamic qualities. Characteristics, such as texture, mineralogy, are innate soil properties determined by the factors of soil formation- climate, topography, vegetation and time. Collectively, these properties determine the inherent quality of a soil. They help compare one soil to another and evaluate soil for specific uses (Jenny, 1941; Sanchez *et al*., 1982). Because these factors are complex and the effects of land-use history may be long lasting, soil quality can be difficult to characterize (Karlen *et al*., 2001). Soil drainage, tillage, and addition of lime and fertilizer have positive effects on soil productivity, whereas soil erosion, loss of organic matter and physical structure, and other degrading processes have negative impacts. Both positive and negative processes occur simultaneously, making it difficult to associate changing yields with certain cultural practices. More recently, attention has been paid to the dynamics of soil quality defined as the changing nature of soil properties resulting from human use and management (Eijsackers, 1998).

It is often difficult to clearly separate soil functions into chemical, physical, and biological processes because of the dynamic, interactive nature of these processes. This interconnection is especially prominent between chemical and biological indicators of soil quality and there is seldom a one-to-one relationship between function and indicator; more likely, a given function (e.g. sustaining biological productivity) is supported by a number of soil attributes, while any given

soil property or process may be relevant to several soil attributes and/or soil functions simultaneously (Harris *et al*., 1996; Burger and Kelting, 1999). For example, many soil chemical properties influence microbiological processes and together with soil physico-chemical processes, they determine the capacity of soil to hold and supply water and nutrients. Another good example of the latter is soil organic matter, which plays a role in almost every soil function (e.g. Henderson, 1995; Harris *et al*., 1996; Nambiar, 1997).

Measurements of soil quality have the potential to reflect the status of soil as an essential resource. To sum up, there are at least five limitations that, if addressed, could bridge the gap between this potential and the current reality described by Jaenicke (1998). (1) Causal relationships between soil quality and ecosystem functions, including biodiversity conservation, biomass production, and conservation of soil and water resources are rarely defined or quantified. True calibration of soil quality requires more than merely comparing values across management systems. (2) Most soil quality indicators have limited power to predict soil responses to disturbance. Although there are many indicators that reflect the current capacity of the soil to function, there are few that can predict the capacity of the soil to support a range of disturbance regimes. (3) Land managers frequently find soil quality monitoring to be inaccessible because the measurement systems are too complex, too expensive, or both. (4) Soil quality measurements are generally presented as 'stand-alone' tools. However, in order to be effective, they need to be integrated with other biophysical and socio-economic indicators. (5) Most current soil quality assessments are point-based, yet ecosystems are generally managed at the landscape level.

In soil research's effort to rate relative performance of a soil in terms of critical functions (whatever the ecological, economical, environmental, or social function(s) we assign to it), we must resort to describing a set of identifiable attributes that such soil must possess in order to perform these functions, and then translate these attributes into first or second-level measurable surrogates (i.e. soil properties or processes). A given function (e.g. sustain biological productivity) is supported by a

number of soil attributes, while any given soil property or process may be relevant to several soil attributes and/or soil functions simultaneously.

I.1.3 Brief introduction of soil degradation in China

This thesis addresses aimed at proposing soil quality indicators for agro ecosystems in Southern China. In the Yingde region, 300 Km north of Guangzhou, land is covered with tea plantations, sometimes 10-30 years old or more, and a mixture of rather diverse cultures, sugarcane, fruit tree plantations (orange), pine forest, separated by bamboo stands or wasteland areas.

Soil degradation is very widespread in China. Since 1978, and the political opening farmland have been cultivated without any interruption and no environmental protective measures. It made the soil seriously degrade and ill irrigation often resulted in salinization (Jiang and Shinaro, 1999). In China, wind erosion mainly happened in north China, concentrated in northest and northwest China (Figure I.1) and the extent of wind erosion (Figure I.2) (Jiang and Shinaro, 1999) were moderate to common in most provinces, the major causes of wind erosion belonged to the agricultural activities, deforestation and overgrazing. From Figure I.1 we can see that from city to city +50km, no matter what type soil degradation, water erosion, wind erosion, chemical deterioration and physical deterioration, the degree and extent of soil degradation had significantly increased. But from city +50km to city to city +50km, it may be the possibility that human activities of agricultural and industrial production mainly concentrated within city +50km. In view of the causes of soil degradation in China, unreasonable agricultural activities and deforestation around city around city area were the major causes.

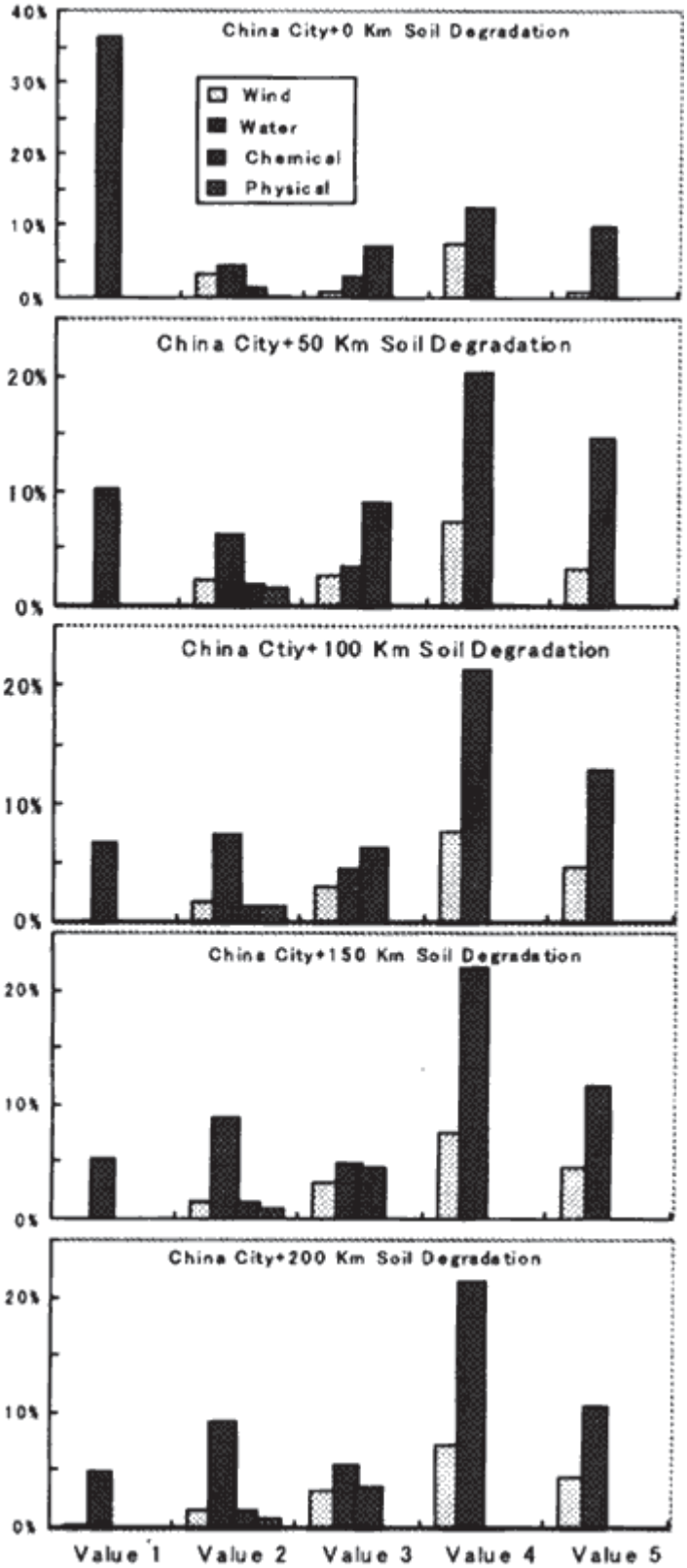


Figure I.1: soil degradation from City to City +200km in China (Jiang and Shinaro, 1999).

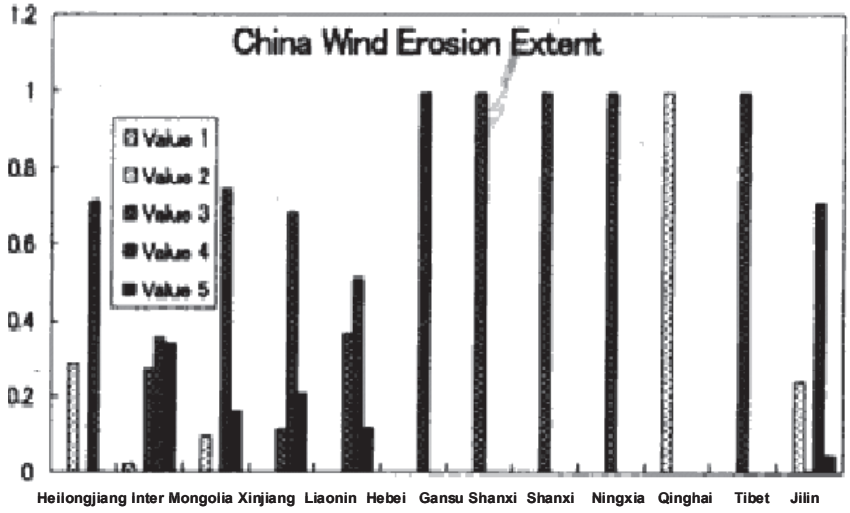


Figure I.2: Wind Erosion in China (Jiang and Shinaro, 1999).

Water erosion happened in every province to some extent in china, but the strongest provinces were Hebei province and Tianjin city in north China, the secondary provinces were Jilin and Liaoning provinces in northeast China, the third were provinces located in coastal region in southeast China (Figure I.3 and I.4) (Jiang and Shinaro, 1999).

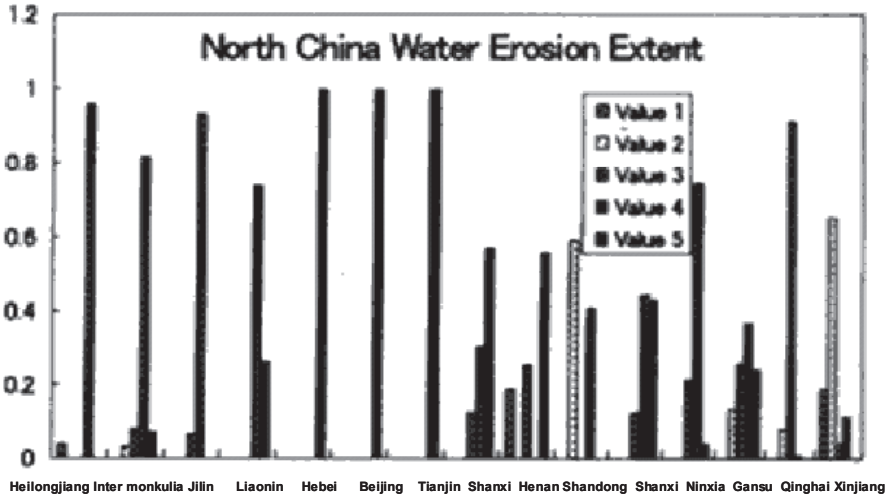


Figure I.3: Water Erosion in North China (Jiang and Shinaro, 1999).

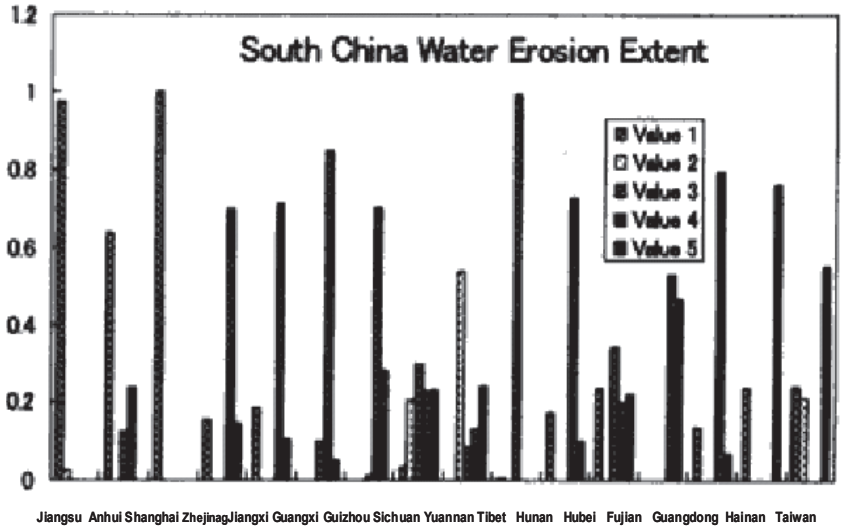


Figure I.4: Water Erosion in South China (Jiang and Shinaro, 1999).

The causes of water erosion were deforestation and agricultural activities, unreasonable irrigation, overusing groundwater, and it made the soil salinization commonly happen in north China. In northeast China, the major cause of water erosion was overgrazing. The major causes in northwest China is deforestation and in southeast China deforestation and agricultural activities.

Chemical deterioration mainly happened in Hebei, Tianjin, Henan, Xinjiang, Gansu, and Inner Mongolia, and in which Hebei province was the most seriously province suffered the chemical deterioration, the secondary provinces ere henna, Shangdong and Xinjiang (Figure I.5). The causes of chemical deterioaration wee unreasonable agricultural activities, overuse groundwater, irrigation and related salinization, etc.

The physical deterioration was limited to Anhui, Henan and Jiangsu provinces; the cause was agricultural activities.

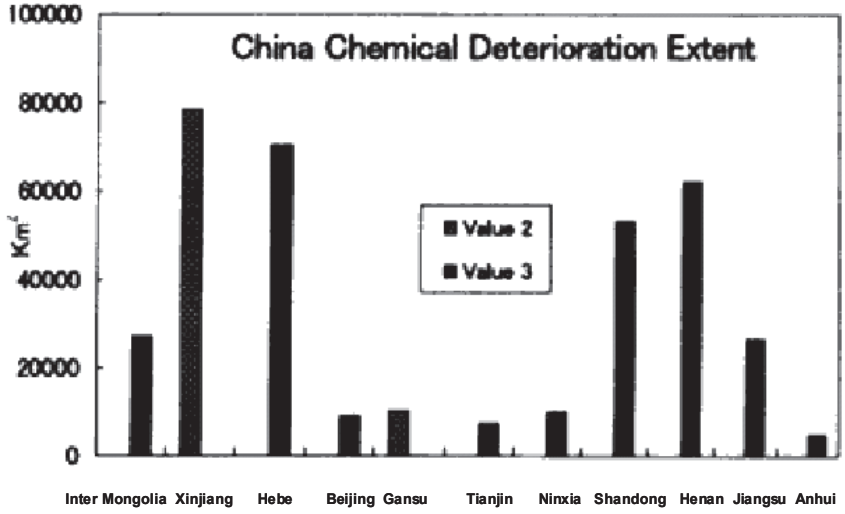


Figure I.5: Chemical Deterioration in China.

Soil in tea gardens in South China had low fertility, this degradation can be seen in the low soil organic matter content, cation exchange capacity, poor and little diverse soil fauna populations and highly acidic pH, and in the high soil compaction, erosion, nutrient leaching. It was similar to the long-term exploitation of soil under the tea gardens in Southern India (Panigrahi, 1993; Senapati *et al*., 1999).

Form the research results, we can get conclusion that in China with economic development, land uses and covers and related environment had greatly been changed. How to rational use land resource and protect the environment as well as keep sustainable development, it is the most important problem that Chinese people has to copy with. In view of analysis and calculated results, most of the results are has to copy with. In view of analysis and calculated results, most of the results are consistent with the actual situation. Because of the data belongs to different periods and the difference of the classification criterion, some results are consistent with the actual situation.

Our study aimed to design a synthetic indicator that allowed quantifying the physical state, chemical fertility, quality and stocks of organic matter, aggregation and morphology in the upper 5cm and diversity and composition of soil

macroinvertebrate communities. These sub-indicators would then be combined into a general index. The general methodology proposed by Velasquez (2004) was used.

Physical quality mainly addresses soil aggregation and the total amount of porosity. General descriptors for this attribute of soil quality are bulk density, total porosity and moisture content that assess void volumes in different ways. Stability of structure and compaction are approached through global measurements of resistance to penetration and shear strength, easy to measure with standard and low cost equipments (To and Kay, 2005; Léonard, J and Richard, G. 2004; Larson and Pierce, 1994; Herrick *et al*., 2001).

Chemical fertility is the ability for soil to provide the basic nutrients necessary to plant growth. Basic measurements of cation concentrations and pH allow separating soils with sufficient concentrations in all macronutrients from unfertile, nutrient poor, soils (Larson and Pierce, 1994; Lavelle and Spain, 2006).

Morphology is an assessment of the contribution of soil aggregates of different sizes and origins (physical or biogenic), plants, gravels and stones and other components to the architecture of the upper cm of soil derived from visual separation of these items. Presence of a large proportion of biogenic aggregates of different sizes rather than physical aggregates or non aggregated soil, invertebrates and roots linked to high biological activity should indicate high quality soils (Blanchart *et al*., 1999; Ponge, 1999; Topoliantz *et al*., 2000)

Organic matter is an important attribute of soil quality for the variety of functions that it has in soils as cation reserve and agent of aggregate stabilization, site for carbon storage and sequestration and as an energetic resource for heterotrophic biological activity. This component of soil quality is assessed through overall contents in C and N, density fractionation that separates short lived light fractions from long lived heavy fractions associated to clay and fine silt fractions and respirometry activities in optimal laboratory incubations that indicate to which extent organic matter is accessible to soil micro-organisms (Marinissen and Hillenaar, 1996; Pulleman *et al*, 2002; Six *et al*., 2002).

Macroinvertebrate communities composition and abundance are indicators of

biological activities, the physical and chemical ecosystem engineering operated by invertebrates themselves, and subsequent associated microbial activities (Lee and Foster, 1991; Pankhurst *et al*, 1995; Lavelle *et al*., 1997; Pulleman *et al*., 2005; Mathieu *et al*., 2005).

The implementation of these indicators was done in the region of Yingde, on a set of 20 plots submitted to different types of land use, tea plantations with diverse degrees of intensification and fertilizer, orange tree plantation, sugarcane, bamboo forest, pine forest and wasteland.

In a second part, we detailed the physical indicators of soil quality and tried to calibrate the soil morphology indicator, mainly based on a visual assessment of soil aggregation with standard physical methods.

I.2 Sampling protocols and treatments

I.2.1 Sites description and sampling

The study sites are located in the Tea Research Institute, Guangdong Academy of Agricultural Sciences (Tea1) and Shangmingxuan Tea Garden area (Tea2, 20 km from Tea1), Yingde, Guangdong Province, south of China (Figure I.6).

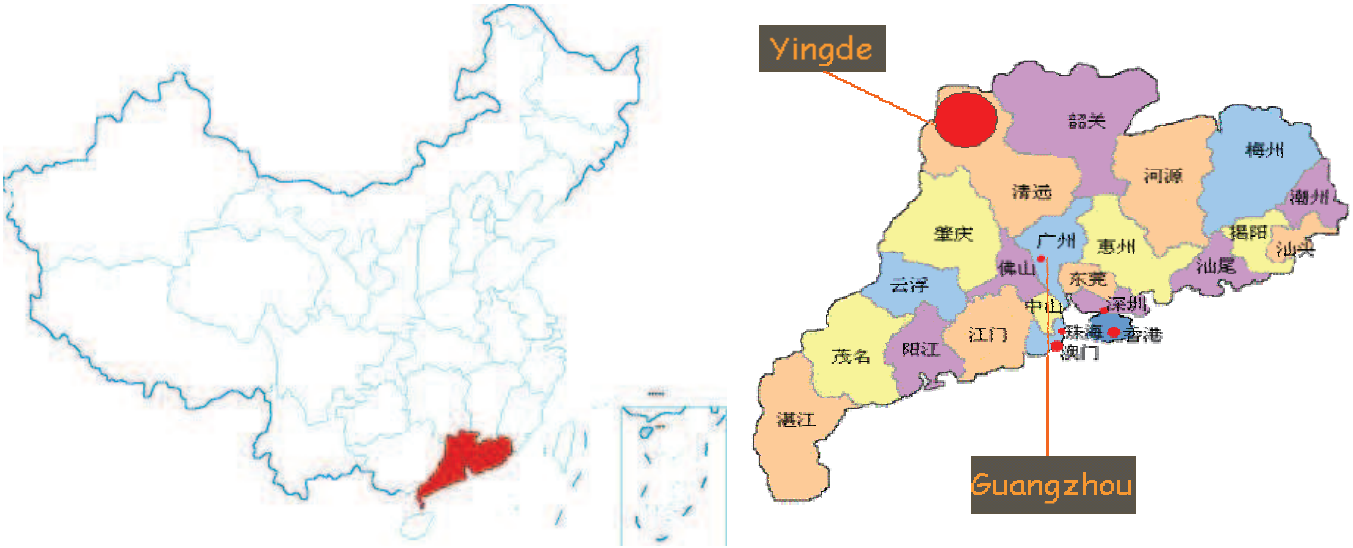


Figure I.6: Location of the study sites.

Climate is subtropical, with an average annual temperature of 20.7℃, average annual sunlight 1700 hours, and an average annual rainfall of 1600 mm, mainly concentrated in the period from March to August. Soils are clayey, acidic, derived from Quaternary red clay (Liu, 1993). Surface soil (0-20cm) has a low organic content (around 1.9%), silt/clay ratio is around 1.0, pH varies from 3.7 in one tea plantation in Tea1 to 7.9 in the orange garden, bulk density ranges from 1.0 to 1.5 g cm^{-3}.

Sampling was carried out in June 2004. 20 sites were selected, 15 tea gardens, 1 sugarcane plantation, 1 orange garden, 1 pine forest, 1 bamboo forest, and a plot of abandoned land (wasteland) (Table I.1). With different land-use histories, fertilizer utilization and soil managements, they are representative of the wide variations observed in the area.

In each site, 5 points were chosen at the center of the sites and at the 4 corners (generally distant 20 to 30 m) to take soil samples.

Table I.1: Sampling sites description.

N°	Plantation	Location	Description
1	Tea1, 1	24°18´24 N, 113°23´19 E	20 years, chemical fertilizer
2	Tea1, 2	24°18´22 N, 113°23´01 E	3 years, chemical fertilizer and manure*
3	Tea1, 3	24°18´21 N, 113°23´01 E	10 years, chemical fertilizer and manure*
4	Tea1, 4	24°18´21 N, 113°23´01 E	10 years, submersed 3 times/10 years, chemical fertilizer and manure*
5	Tea1, 5	24°18´21 N, 113°23´01 E	Replanted 2 years ago, chemical fertilizer and manure*
6	Tea1, 6	24°18´24 N, 113°23´19 E	20 years, chemical fertilizer and manure*
7	Tea1, 7	24°18´09 N, 113°23´08 E	10 years, chemical fertilizer and manure*
8	Tea1, 8	24°18´09 N, 113°23´08 E	10 years, chemical fertilizer and manure*
9	Tea1, 9	24°18´09 N, 113°23´08 E	10 years, chemical fertilizer and manure*
10	Tea1, 10	24°18´22 N, 113°23´01 E	15 years, chemical fertilizer and manure*
11	Tea1, 11	24°18´22 N, 113°23´01 E	15 years, chemical fertilizer and manure*
12	Tea2, 12	24°22´13 N, 113°27´55 E	Nearly 30 years, manure of chicken and cow**
13	Tea2, 13	24°22´13 N, 113°27´55 E	Nearly 30 years, urea and spray fertilizer for leaves***
14	Tea2, 14	24°22´13 N, 113°27´55 E	Nearly 30 years, urea and spray fertilizer for leaves***
15	Tea2, 15	24°22´13 N, 113°27´55 E	Nearly 30 years, chicken manure ****
16	Sugarcane	24°17´55 N, 113°23´04 E	3 years, residues
17	Orange	24°17´55 N, 113°23´04 E	5 years, manure, chemical fertilizer and lime****
18	Pine	24°18´21 N, 113°23´01 E	Artificial secondary, less than 10 years, no fertilizer
19	Bamboo	24°22´13 N, 113°27´55 E	20 years, no fertilizer
20	Wasteland	24°18´21 N, 113°23´01 E	No fertilizer

* Organic manure applied once every 3-4 years, chemical fertilizers 3 times a year and pesticides5-6 times a year

** Chicken and cow manure and P fertilizer applied once a year

***Urea and spray fertilizer for leaves were applied 3 times a year

**** Manure and fertilizer were applied once year

I.2.2 Statistic analysis

Principal component analysis (PCA, Martens and Naes, 1989) was applied in our data analysis. PCA allows to identify patterns in complex data sets, and express the data in such a way as to highlight their similarities and differences. PCA decomposes a data matrix X of rank h, as a sum of matrices of rank 1. The rank indicates the number of linearly independent vectors of a matrix. The new rank 1 matrices are vector products of the score vectors, t, and loading vectors, p, as shown in Eq:

$X = t_1 p_1' + t_2 p_2' + \bullet \quad \bullet \quad \bullet + t_h p_h'$

These vectors can be calculated by a least squares fit (singular value decomposition—SVD). The new coordinates of the system, named Principal Coordinates, are mutually orthogonal and thus not correlated and successively explain decreasing proportions of the residual variation. Usually, only the first few PCs account for the greatest amount of total data variance and can be utilized to represent the whole data set in a simpler manner.

The other main advantage of PCA is that once found these patterns in the data, the original set of variables can be reduced into a small number of identified factors without loosing much information.

PCA was used to examine whether disturbed and control plots at different sites differ on the basis of the different sets of variables that were measured in the field. A correlation matrix PCA (correlation circle) was also calculated to reveal relations between variables, and between the variables and the extracted factors.

While univariate methods are appropriate when only one variable is measured systematically for several samples, a better understanding of soil-ecosystem

processes requires the measurement of many variables and therefore the use of multivariate analytical tools (Sena *et al*. 2002).

Grouping of analytical data is possible either by means of clustering methods or projecting the high dimensional data onto lower dimensional space. It is obvious that no isolated property can provide an extensive picture of the quality of a specific soil (Torstensson *et al*., 1998).

The use of PCA and other methods of multivariate analysis has allowed to find the resolution of several problems, for example the determination of management discriminant properties in semiarid soils (Quiroga *et al*., 1998), identification of sources of soil pollutants (Carlosena *et al*., 1998), assessment of the tillage impacts on soil quality (Wander and Bollero, 1999) or the relation of soil compactibility to physical and organic properties (Ball *et al*., 2000). Bentham *et al*. (1992) used principal component analysis and other statistical clustering techniques to choose variables best representing the progress of soil restoration efforts.

Once the main factors (Principal Components) have been chosen, the data can be projected onto the new reduced space. A score plot depicts the linear projection of objects, allowing the observation of the relative localization and grouping of objects in factorial spaces.

The correlation of variables is described by the cosine of the angle between the loading vectors. The smaller the angle, the higher the correlation between features. Uncorrelated variables are orthogonal to each other. Coordinates along the considered PC are a measure of the importance of a feature for the PC model. Projections close to the origin of the coordinate system represent unimportant variables or items as regards the factors represented. The interactive study of score and loading vectors, better visualized through the plots, permits the visualization of the influence of each variable on each object (Gabriel, 1971). If a variable is close to an object, it likely has a direct influence on it. Conversely, if a variable is distant from an object, it will have high inverse influence on it. The variable and object projections onto the axes provide their relative contributions for the corresponding PCs.

The multivariate method PCA was applied to the mean values of variables measured in 5 samples of each site. The data were analyzed using the ADE-4 program (Thioulouse *et al*., 1997). In our study, the five groups of soil parameters (chemical, physical, soil organic matter, soil macrofauna and soil morphology) were analysed by PCA; we calculated how much these parameters distinguish soils from different sites and sub-indicator of chemical, physical, soil organic matter, soil macrofauna and soil morphology were calculated based on these results. Finally, a general soil quality indicator was calculated with all five sub-indicators integrated into one value for each site (Velasquez, 2004).

I.3 Physical properties

Physical properties are major indicators of the ability of soils to provide very important ecosystem services; they determine their capacity to infiltrate, store, purify and release water, they also indicate their resistance to erosion and availability of water and air for living organisms.

I.3.1 Introduction

Table I.2 is a list of physical indicators that has been proposed by various researchers (Schoenholtz *et al*, 2000). Basic soil physical indicators like soil texture and depth may be responsible for different intrinseque soil qualities among soil types.

Soil texture, and especially the amount and quality of clay minerals, is the most fundamental soil physical property controlling water, nutrient, and oxygen exchange, retention, and uptake. The fine soil fraction significantly influences aggregate stability. In coarse-textured soils, soil organic carbon that comprise the only colloid fraction has a greater influence on structure than in fine textured soils; the type of clay may sometimes be more important than the amount in determining aggregation since 2:1 type minerals are better at glueing particles than 1:1 type (Kay, 1998). High clay concentration (and high clay quality, that is predominance of 2:1 type over 1:1) is also associated with increased SOC stabilization (Sollins *et al*., 1996).

Soil bulk density varies among soils of different textures, structures, and organic matter content, but within a given soil type, it can be used to monitor the degree of soil compaction and flooding. Changes in soil bulk density affect a host of other properties and processes that ultimately influence water and oxygen supply. However, a measure of soil strength using a cone penetrometer may be the best way to index the influence of soil density on root proliferation and growth (Powers *et al*., 1998). Bulk density is, nonetheless, needed in a minimum data set of soil quality indicators to convert mass estimates of soil components to volume estimates.

Table I. 2: (Schoenholtz et al, 2000)

Physical soil quality indicators recommended or used by soil researchers

Indicators of soil quality	Role or contribution to soil quality	Type or units of measure	Recommended or used by
Static indicators			
Soil texture	Retention and transport of water and nutrients	%sand, silt, clay	Doran and Parkin, 1994
Soil depth, topsoil depth	Total nutrient, water, oxygen availability	Thickness (cm)	Larson and Pierce, 1991; Arshad and Coen, 1992; Doran and Parkin, 1994; Gomez et al., 1996
Soil bulk density	Root growth, rate of water movement, soil volume expression	Core sampling ($g\ cm^{-3}$)	Larson and Pierce, 1991; Arshad and Coen, 1992; Doran and Parkin, 1994; Kay and Grant, 1996
Available water holding capacity	Plant available water, erosivity	Water (cm), 33>1500 kPa	Larson and Pierce, 1991; Arshad and Coen, 1992; Doran and Parkin, 1994; Kay and Grant, 1996
Soil roughness	Erosivity, soil tilth	Tilled/flat ratio	Larson and Pierce, 1991
Saturated hydraulic conductivity	Water and air balance, hydrology regulation	Water flow in soil column ($cm^3\ s^{-1}$)	Larson and Pierce, 1991; Arshad and Coen, 1992
Soil loss	Total soil, water, nutrients for plant use	Soil loss (cm)	Harris et al., 1996; USDA, 1991
Soil strength	Root growth	Resistance to penetration (Mpa)	Powers et al., 1998; Burger and Kelting, 1998
Porosity	Water/air balance, water retention, root growth	%soil volume	Powers et al., 1998
Aggregate stability and size distribution	Root growth, air/water balance	Wet-sieving method	Arshad and Coen, 1992; Kay and Grant, 1996
Soil tilth	Root growth	Index (Singh et al., 1993)	Papendick, 1991; Burger and Kelting, 1998
Dynamic indicators			
Least limiting water range	Water/air balance, root growth	Water retention curves, penetration resistance	Arshad and Coen, 1992; da Silva et al., 1994; Kay and Grant, 1996; Burger and Kelting, 1998
Trafficability	Ability to operate	Model (Wosten and Bouma, 1985)	Wagenet and Hutson, 1997
Leaching potential	Transport, transform, attenuate applied chemicals	Model (Petach et al., 1991)	Wagenet and Hutson, 1997
Erosion potential	Available soil, water, nutrient, root growth, environmental concern	WEPP (Nearing et al., 1989) SEP (Timlin et al., 1986)	Wagenet and Hutson, 1997

In our study, we selected soil texture, bulk density, soil moisture and soil strength measured with a cone penetrometer to describe soil physical properties.

I.3.2 Materials and methods

Soil samples for texture analysis were take at 0-10 cm and 10-20 cm depth, air-dried and sieved at 2mm. Analysis was done with the pipette method. Soil bulk density was measured on samples collected with 2.5×5 cm annular cylinders; samples were weighted after 24 hours drying in an oven at 105℃. Soil moisture was measured at the same time. Soil strength was measured in site with a cone penetrometer.

I.3.3 Results and discussion

Physical variables exhibited rather large variations across the sites with values from 0.97 to 1.49 in bulk density, 15.1% to 34.1% in water content, 1.76 to 30.58kg cm^{-2} in soil strength, 8.8% to 32.1% in sand percent, 25.9% to 58.5% in silt percent and 18.2% to 62.4% in clay percent (Annexe, Table 1).

I.3.3.1 Soil texture

Sand proportion varied from 8.8% (Tea1, 1, 0-10 cm) to 32.1% (Sugarcane plantation, 10-20 cm); silt percent varied from 25.9% (Tea1, 1, 10-20 cm) to 58.5% (Orange plantation, 0-10 cm) and clay percent varied from 18.2% (Sugarcane plantation, 10-20 cm) to 62.4% (Tea1, 10-20 cm)(Figure I.7). Overall, soils from the Tea 1 area tended to have finer structure that Tea 2 and sites with other types of cropping systems.

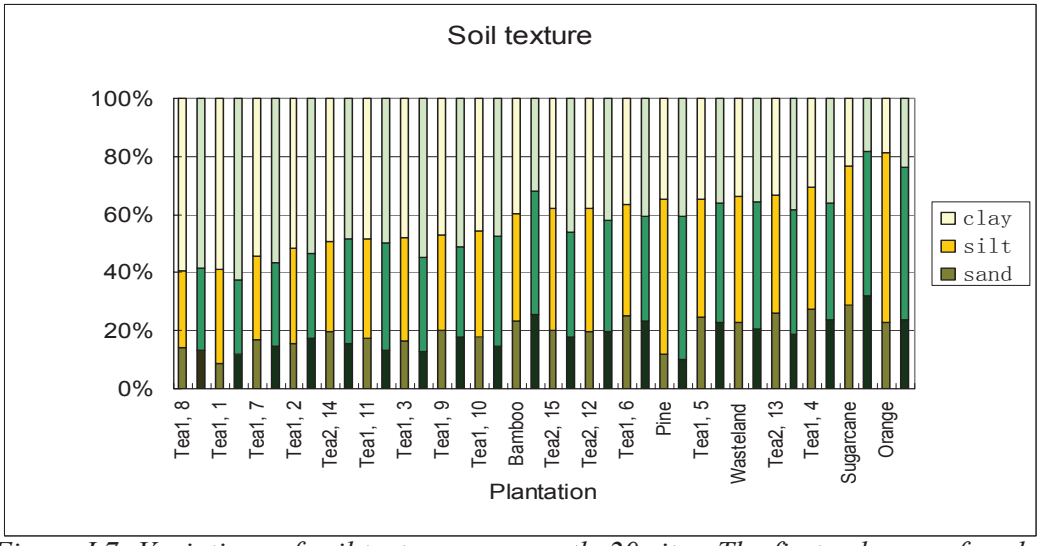


Figure I.7: Variations of soil texture e among the20 sites. The first columns of each site are values for soil samples taken from 0-10 cm and second columns are values for soil samples taken from 10-20 cm.

Orange plantation had the highest silt percent and Tea plantation Tea1, 8 in tea institute had the highest clay percent of all the 20 sites.

I.3.3.2 Soil bulk density

Bulk density varied from 0.97g cm^{-3} in Bamboo to 1.49 g cm^{-3} in Wasteland (Figure I.8).

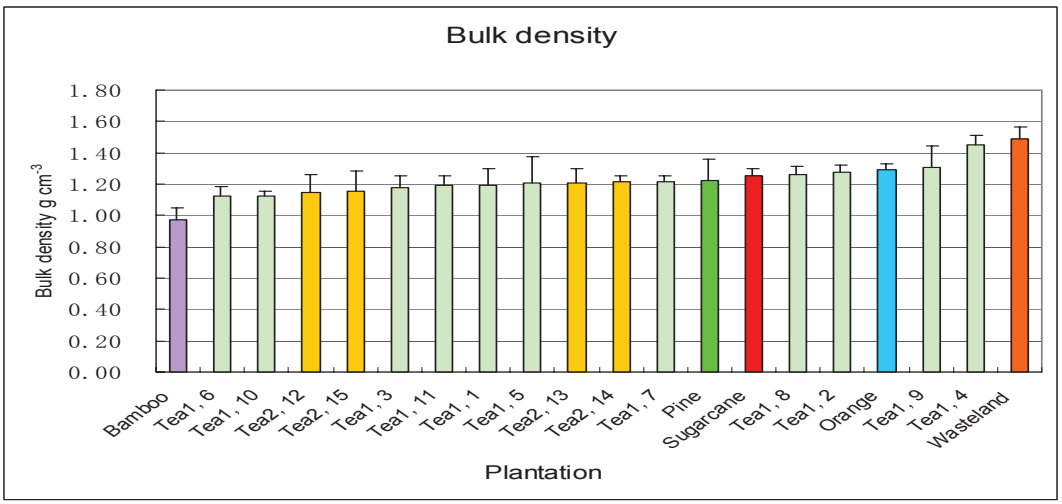


Figure I.8: Variations of soil bulk density among the 20 sites (0-5 cm depth).

Soil bulk density was around 1.20 g cm^{-3} for most of the sites. Wasteland had the highest bulk density (1.49 g cm^{-3}) than other sites; this was probably due to its high content in fine sands, limited soil faunal activity and regular flooding (3 times in 10 years). Tea plantation Tea1, 4 in Tea1 had a high bulk density (1.45 g cm^{-3}) probably due to its same regular flooding of wasteland.

I.3.3.3 Soil strength

Soil strength varied largely, from 1.76 (Tea1, 2, 0-10cm) to 30.58 kg cm^{-2} (Tea1, 4, 10-20 cm)(Figure I.9).

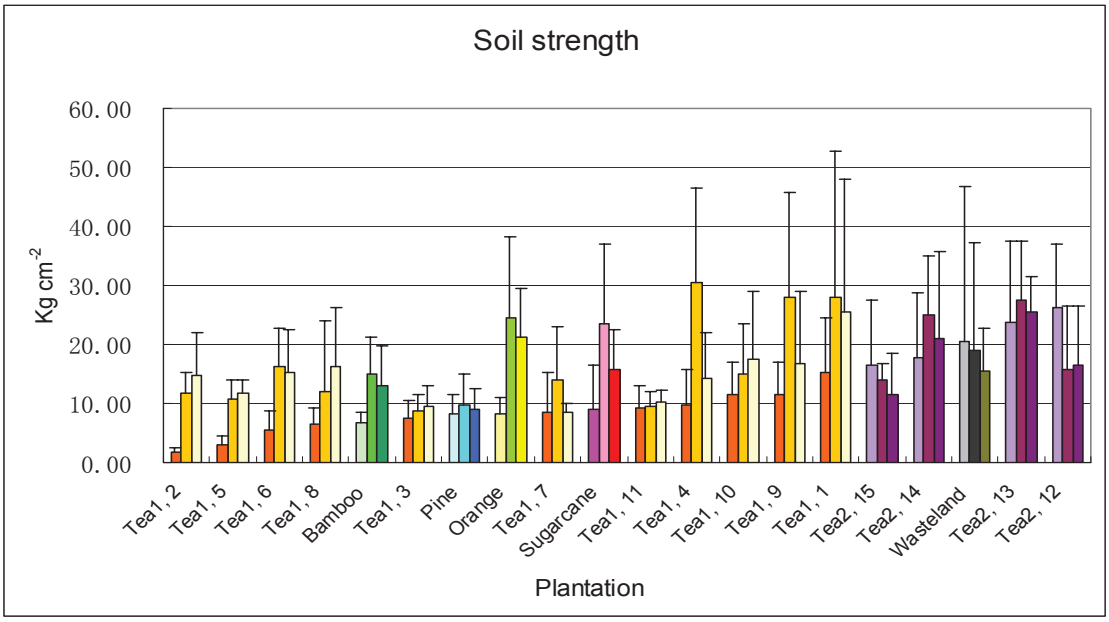


Figure I.9: Variations of soil strength among the 20 sites. The first columns of each site are values for measurements done at 0-10 cm, second columns at 10-20 cm and third column, at 20-30 cm.

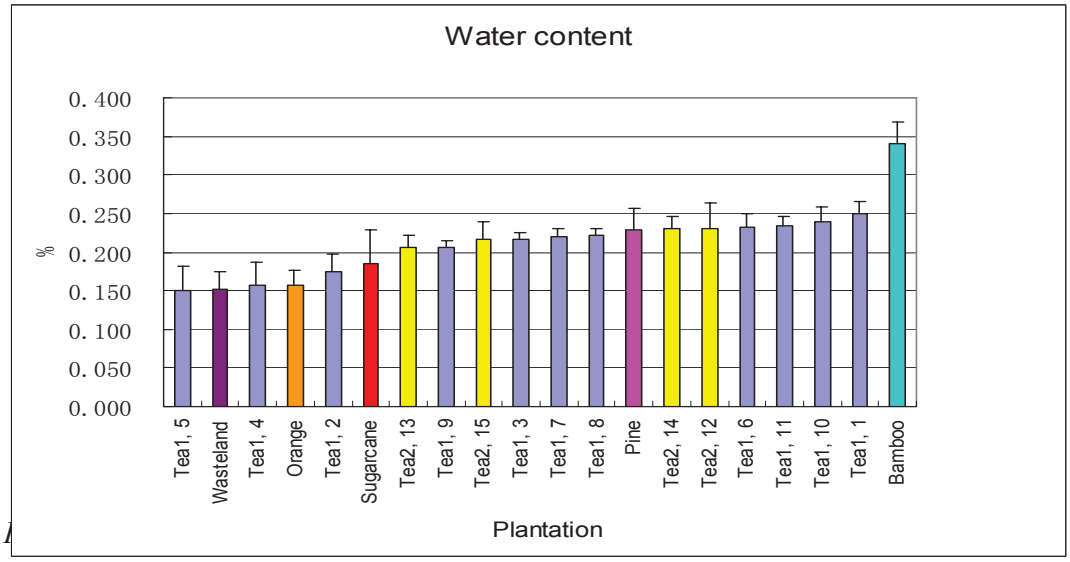
Tea1, 2 had a very low strength in surface soil; it had been created from wasteland 3 years ago, manure was applied at soil surface a few days before our sampling. Site Tea1, 4 had been flooded 3 times in 10 years, which could have made soil harder.

Soil strength is an important parameter of soil quality for its effect on root proliferation. This parameter however is also dependent on soil moisture and changes

with seasons and specific conditions at the time of the sampling. Sampling of the 20 sites was done during 20 days and the weather changed (rained or not) when different sites sampling was done. This probably explains part of the large variations observed from one site to another.

I.3.3.4 Soil water content

Soil water content varied from 15.1% (Tea1, 5 and wasteland) to 34.1% (Bamboo) (Figure I.10).



Soil water content (soil moisture) varied according to texture, structure, and organic matter content. Climate conditions at the time of sampling also had some effect on the result. Bamboo plantation had much higher water content (34.1%) than all of the other sites.

I.3.4 Multivariate analyses (PCA) of physical parameters

PCA analysis was performed on the set of six variables in the 20 sampled sites (Table I.3).

Table I. 3: Correlation matrix of the 6 physical parameters measured in the 20 sites (rx1000).

Correlation matrix						
	Bulk density	Water%	Soil strength	Sand%	Silt%	Clay%
Bulk density	1000					
Water%	-651	1000				
Soil strength	238	39	1000			
Sand%	326	-322	65	1000		
Silt%	279	-345	96	386	1000	
Clay%	-356	400	-100	-752	-899	1000

Bulk density and soil water content had significant negative correlation, while soil clay content was negatively correlated with sand and silt content, as expected.

The first two factors respectively explained 49.1 and 18.8% of total variance, the next factors being much less important (Table I.4).

Table I.4: Inertia of Principal components of soil physical parameters analysed in the 20 sites.

Inertia							
Factor	Eigenval.	Inertia%	Sum Inertias	Factor	Eigenval.	Inertia%	Sum Inertias
1	2.94E+00	0.4905	0.4905	2	1.13E+00	0.188	0.6785
3	1.02E+00	0.17	0.8485	4	6.22E-01	0.1037	0.9522
5	2.87E-01	0.0478	1	6	0.00E+00	0	1

Table I.5: Absolute contributions of the first two principal components of all physical variables analysed in the 20 sites (all contributions are in 1/10000).

Variable contributions						
	Bulk density	Water%	Soil strength	Sand%	Silt%	Clay%
F1	-1452	1533	-106	-1874	-2147	2885
F2	-3853	2011	-1176	488	1214	-1255

Factor 1 was largely determined by texture and opposed sites with high clay and water contents to sites with silty and sandy soils and high bulk density. Factor 2 was more associated to bulk density.

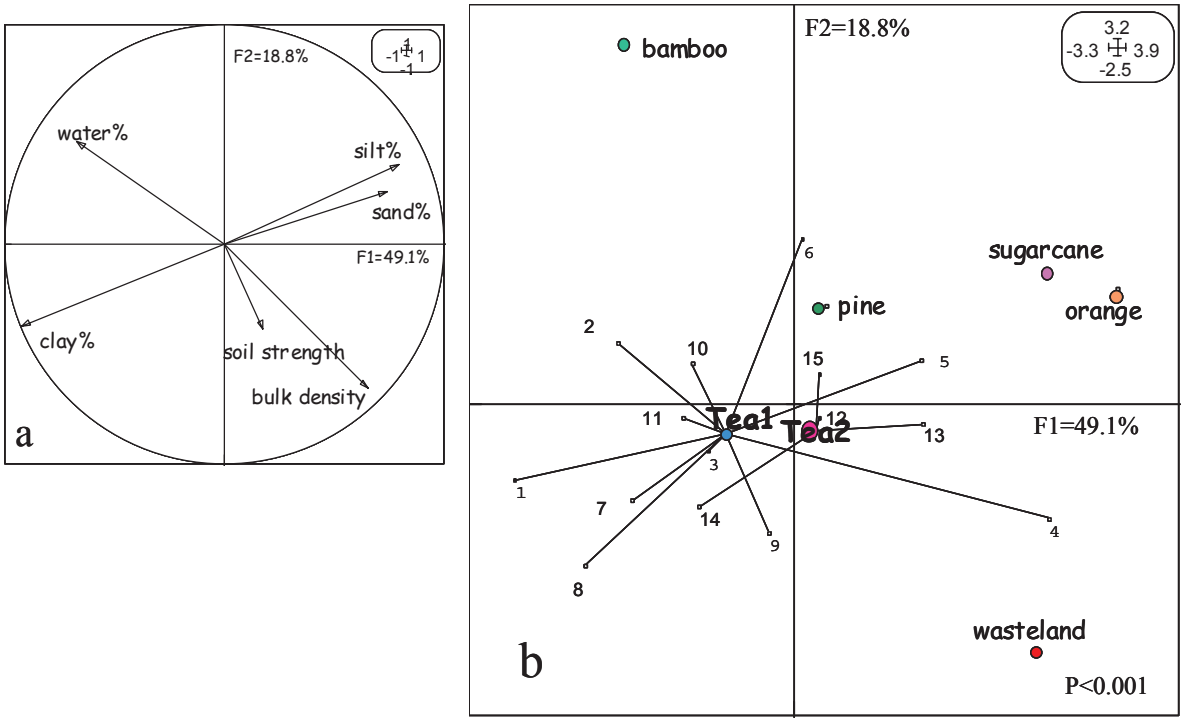


Figure I.11: Ordination of sites by PCA analysis of bulk density, water content, soil strength, sand, silt and clay content.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 6 physical parameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together 67.9% of the inertia.

Sugarcane plantation, Wasteland and Orange plantation with coarse textured soils were far projected along axis 1. Tea plantations of the first group (tea Institute at Yingde) - especially Tea1, 1 and Tea 1, 8 - had finer textured soils than the ones of group 2. Separation of sites according to their physical parameters was significant ($p<0.001$).

Bamboo forest, Sugarcane, Orange and Pine forest with high bulk density and soil strength were separated along factor 2, from tea plantations and wasteland that had much less compact soils. Tea1, 4 was located far from other tea plantations in Tea1 in the factorial plane F1F2 for its high bulk density (1.45g cm^{-3}) and soil strength. Tea1, 1, and Tea1, 8 had higher clay percent (58.7% and 59.3% respectively) than other sites.

I.3.5 Calculation of the Physical sub-indicator

Multivariate analyses (PCA) on physical parameters allowed to ordinate the 20 sites along the different factors extracted and to evaluate the absolute contributions of all physical variables to principal components.

I.3.5.1 Selection of the most discriminating variables and homothetic transformation of original data between 0.1-1.0

Examination of the absolute contributions of physical parameters to the first two principal components lead us to select parameters with contributions more than half of the maximum contribution value of factor 1 and 2 to compose a new data set. Bulk density, water content, sand, silt and clay percent were chosen as main characteristics, while soil strength was wiped off (Table I.5).

In our study, since the variables have different natural scales, parameters were transformed into values between 0.1 and 1.0, with two different formulas:

$$Y = 1.1 - (0.1 + (X-b)/(a-b) \times 0.9) \quad \text{(I-1)}$$

$$Y = 0.1 + (X-b)/(a-b) \times 0.9 \quad \text{(I-2)}$$

Formula (I-1) was applied to the parameters that have opposite variations as compared to soil quality. This was in the case for bulk density and soil strength. The other formula (I-2) was applied to all the other parameters that varied in the same sense as soil quality. Values a, b are the maximum and minimum value for each parameters of all sites (Annexe, Table 2).

I.3.5.2 Design of the physical sub indicator

The contribution of each selected parameter to the soil physical indicator was determined by the product of its reduced value by its contribution to factors 1 and 2, multiplied by the proportions of variance explained by factors 1 and 2 respectively

The sum of the products for all the variables selected provides the raw value of the indicator. Further reduction of these values in the 0.1 to 1.0 range of variation yields the values of the physical sub indicator for each site.

Sub-indicator (SI) = $\sum$i,j,k… (reduced value of Var. i × (absolute contribution (w) of Var. i to F1 × inertia explained by F1) + (absolute contribution (w)

(I-3)

i, j, k.. are variables selected for their weights on axis > 50% the weight of the most influencial variable.

For example:

Physical sub-indicator of Tea1, 1

=0.80×(-1452×0.49-3853×0.19)+0.57×(1533×0.49+2011×0.19)+0.10×(-1874×0.49+488×0.19)+0.26×(-2147×0.49+1214×0.19) + 0.99×(2885×0.49-1255×0.19)

= 365.92

The same calculation was made for all 20 sites. Maximum and minimum values of the raw index values are 611.07 and –1798.59. Raw values are further transformed by formula (I-1) into values between 0.1 and 1.0 for all sites (Annexe, Table 2).

The highest physical sub-indicator was found in orange plantation while the minimum value was observed in tea plantation Tea1, 8. Orange plantation had a highest silt percent (58.5%) than other sites for example, Tea1, 8 with a very high clay percent (59.3%). Orange plantation and tea1, 8 had similar bulk density (1.29 and 1.26 g cm^{-3} respectively), difference of physical sub-indicator may attribute to different silt and clay content.

I.4 Chemical properties

I.4.1 Introduction

Soil quality is largely determined by soil function. A clear example of this is the relationships among chemical and biological indicators of soil quality. Soil organic matter, for example, influences almost all soil functions, many soil chemical properties and directly determines biogeochemical processes, e.g. nutrient and carbon cycling. These processes in turn, together with soil physical and chemical processes determine (1) the capacity of soils to hold, supply, and cycle nutrients (including carbon), and (2) the movements and availability of water.

Soil chemical properties can be divided into static (i.e. point-in time) and dynamic (i.e. process-related) parameters, They can further be grouped into parameters related to soil carbon status, soil acidity, and measures of nutrient availability. Soil pH determines the chemical environment and ionic balances in chemical reactions with direct effects on nutrient availability. Aune and Lal (1997) found that the composition of the exchange complex (exchangeable K^+, Na^+, Ca^{2+}, Mg^{2+}) was a better index of base cation availability than CEC itself, in acid tropical Ultisols ans Oxisols (Aune and Lal, 1997). CEC is often considered as a critical attribute in the assessment of the capacity of an agricultural soil to hold and supply nutrients (Larson and Pierce, 1994).

In our study, we selected soil exchangeable potassium, calcium, magnesium and pH as descriptors of soil chemical properties (Table I. 6).

Table I.6: 4 chemical parameters selected.

Chemical variables		
1	K^+	Exchangeable potassium (mg kg^{-1})
2	Ca^{2+}	Exchangeable calcium (mg kg^{-1})
3	Mg^{2+}	Exchangeable magnesium (mg kg^{-1})
4	pH	pH

I.4.2 Materials and methods

Soil samples for chemical analyses were taken at 0-10 and 10-20 cm depth, air-dried and sieved at 2 mm. Exchangeable K^+, Ca^{2+} and Mg^{2+} were extracted by 1.0 mol L^{-1} NH_4OAc (ammonium acetate), and measured with an AAS (SOLAAR S4) apparatus. Soil pH was determined in 1:2.5 (w/v) soil: solution ratio by pH meter.

I.4.3 Results and discussion

Chemical variables exhibited rather large variations across the sites (*Annexe, Table 3*) with values from 1.6 to 228.6 mg kg^{-1} in K^+, 164 to 2334.4 mg kg^{-1} in Ca^{2+}, 11.4 to 88.2 in Mg^{2+} mg $kg^{-1}$and 3.74 to 8.29 in pH.

I.4.3.1 Soil pH

Soil pH varied from 3.74 in the tea plantation Tea1, 6 (0-10cm) to 8.29 in the Orange plantation (10-20cm) (Figure I.12).

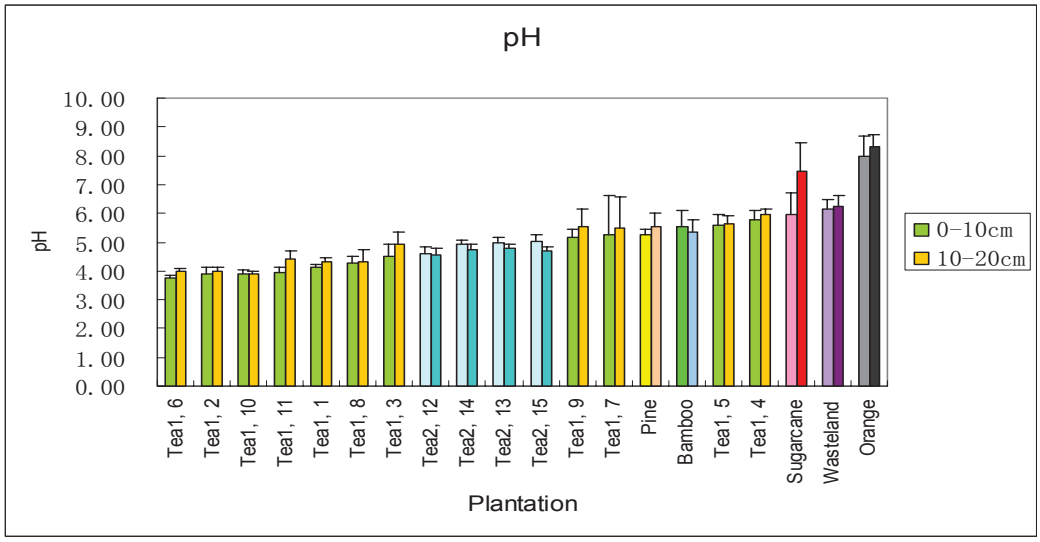


Figure I.12: Variations of soil pH among the 20 sites. The first columns of each site are values for soil samples taken from 0-10 cm and second columns are value for soil samples taken from 10-20 cm.

Soils of tea plantations were more acid than other plantations, pH of orange and sugarcane plantation were significantly higher than others. Lime had been applied in

orange garden once a year together with N, P, K fertilizers. In sugarcane, plant residues are applied on soil surface, which enriches carbon content and changes soil pH.

I.4.3.2 Exchangeable K^+

Exchangeable K^+ concentration was minimum in the wasteland (1.6 mg kg^{-1}, 10-20 cm) and maximum in the orange plantation (228.6 mg kg^{-1}, 0-10 cm) (Figure I. 13).

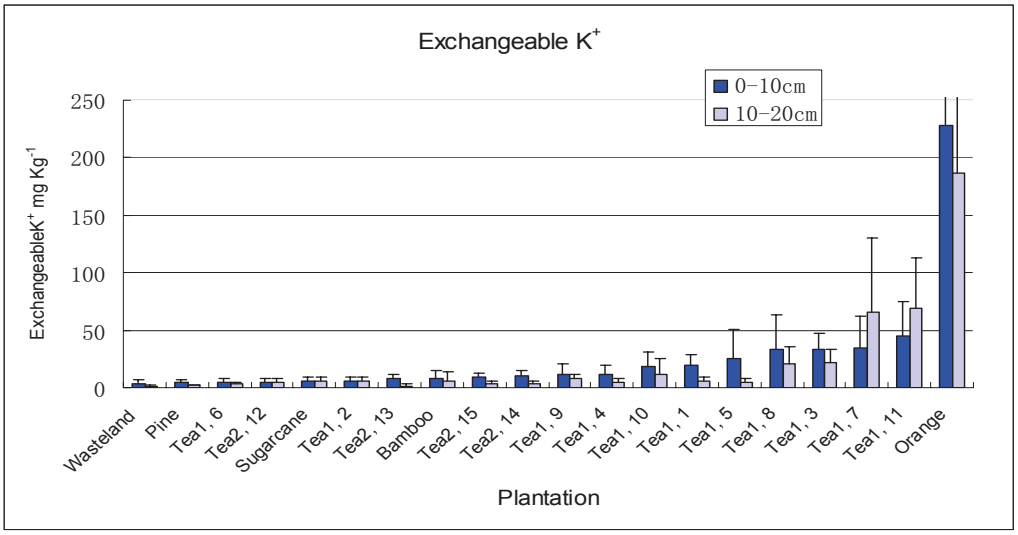


Figure I.13: Variations of soil exchangeable K^+ among the 20 sites. The first column of each site are values for soil samples taken from 0-10 cm and second columns are value for soil samples taken from10-20 cm.

Orange plantation had much higher Exchangeable K^+ than other sites, because of yearly N, P, K fertilizers and lime applications; it was the only site where lime was applied, with significant effects on pH and cation availability. Tea plantations Tea1, 7 in group 1 had higher Exchangeable K^+ than other tea plantations, chemical fertilizers was applied two weeks before the sampling.

I.4.3.3 Exchangeable Ca^{2+}

Exchangeable Ca^{2+} concentration was minimum in Tea1, 2 (164 mg kg^{-1}, 0-10 cm) and maximum in the orange plantation (2334.4 mg kg^{-1}, 10-20 cm) (Figure I.14).

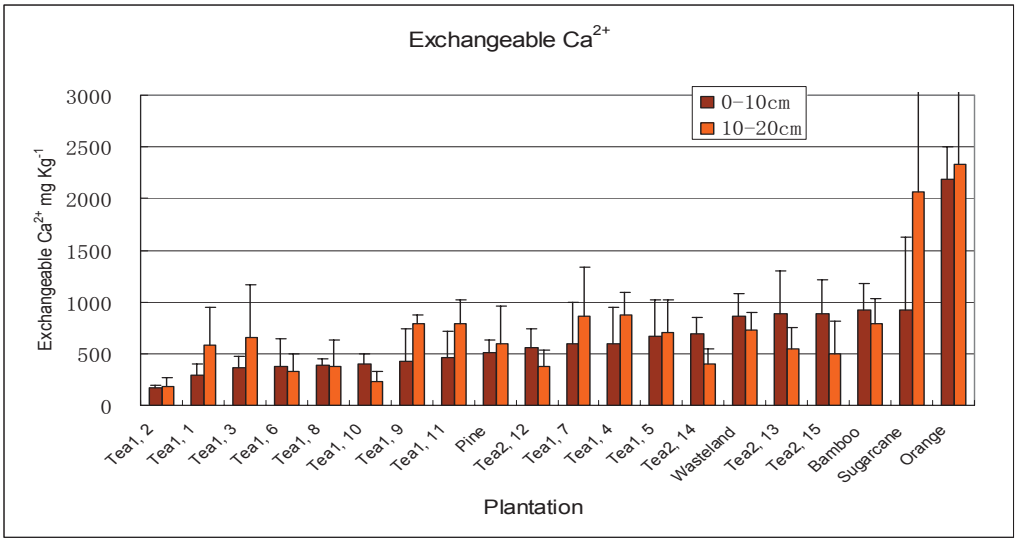


Figure I.14: Variations of soil exchangeable Ca^{2+} among the 20 sites. The first column of each site are values for soil samples taken from 0-10 cm and second columns are value for soil samples taken from 10-20 cm.

Orange and Sugarcane plantation had much higher Exchangeable Ca^{2+} than other sites, because of yearly N, P, K fertilizers and lime applications in orange, for sugarcane, much of residues was applied every year.

I.4.3.4 Exchangeable Mg^{2+}

Exchangeable Mg^{2+} concentration was minimum in Tea1, 2 (11.4 mg kg^{-1}, 0-10 cm) and maximum in Tea1, 7 (88.2 mg kg^{-1}, 10-20 cm) (Figure I.15).

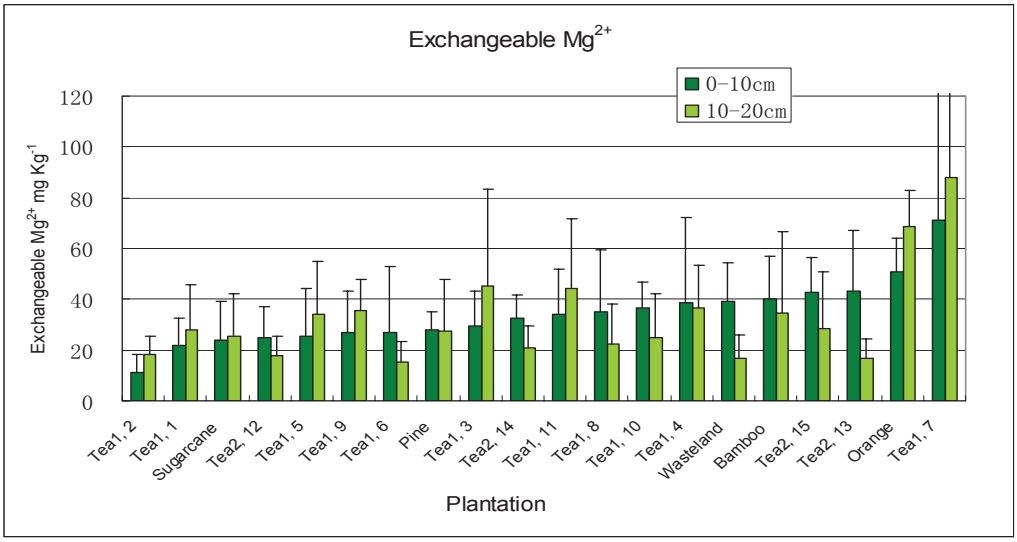


Figure I.15: Variations of soil exchangeable Mg^{2+} values in the 20 sites. The first column of each site are values for soil samples taken from 0-10 cm and second columns are value for soil samples taken from 10-20 cm.

Tea plantation Tea1, 7 in Tea institute (Tea1) had much higher Exchangeable Mg^{2+} than other sites, chemical fertilizers was applied two weeks before the sampling. Orange plantation had higher Exchangeable Mg^{2+} because of fertilizer application.

I.4.4 Multivariate analyses (PCA) for chemical parameters

Correlations among the 4 chemical parameters were computed with the ADE-4 program (Table I.7).

Table I.7: Correlation matrix of the 4 chemical parameters measured in the 20 sites (rx1000).

Correlation matrix				
	K^+	Ca^{2+}	Mg^{2+}	pH
K^+	1000			
Ca^{2+}	774	1000		
Mg^{2+}	373	473	1000	
pH	608	878	416	1000

Soil pH had significant positive correlations with exchangeable K^+ and Ca^{2+}. Application of fertilizers of K and Ca impacts soil acidity.

The first and second principal components explained 70.2% and 17.7% of the total variance respectively (Table I.8).

Table I.8: Inertia of Principal component of soil chemical parameters analysed in the 20 sites.

Inertia							
Factor	Eigenval.	Inertia%	Sum Inertias	Factor	Eigenval.	Inertia%	Sum Inertias
1	2.81E+00	0.7018	0.7018	2	7.07E-01	0.1767	0.8785
3	4.01E-01	0.1002	0.9787	4	8.51E-02	0.0213	1

Table I.9: Absolute contributions of the first two principal components of all chemical variables analysed in the 20 sites (all contributions are in 1/10000).

Variable contributions				
	K^+	Ca^{2+}	Mg^{2+}	pH
F1	2506	3256	1406	2830
F2	-706	-346	8504	-402

Factor 1 was largely determined by exchangeable K^+ and Ca^{2+}, and opposed sites with high pH to other sites. Factor 2 was more associated to exchangeable Mg^{2+}.

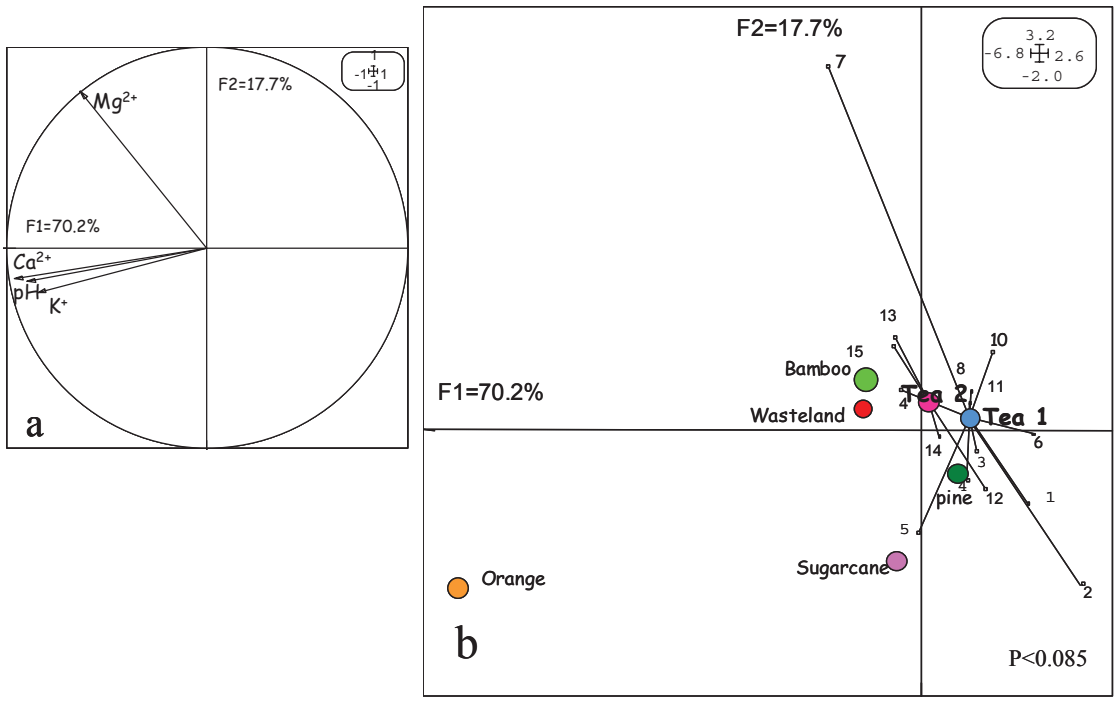


Figure I.16: Ordination of sites by PCA analysis of soil pH, exchangeable K^+, Ca^{2+} and Mg^{2+}.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 4 chemical parameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was almost significant. Factors 1 and 2 explain together 87.9% of the inertia.

Separation of sites according to the soil chemical quality by multivariate PCA was almost significant ($p<0.085$). According to chemical properties, orange and Tea1, 7 were clearly separated from other sites.

Orange was far projected on axis 1, which separates sites according to exchangeable K^+ and Ca^{2+} and pH. Orange had the highest pH value (pH=7.97 and 8.29 for soil samples taken from 0-10cm and 10-20 cm), and pH had significant positive correlations with exchangeable K^+ and Ca^{2+}, orange had the highest

concentration in exchangeable K^+ and Ca^{2+} (228.6 mg kg^{-1}, 0-10cm; 2334.4 mg kg^{-1}, 10-20cm). This site had been planted to orange trees 5 years ago and manure, chemical fertilizer and lime had been applied every year. Tea1, 7 had a high positive coordinate along axis 2, which separates sites according to exchangeable Mg^{2+}. Tea1, 7 had the highest exchangeable Mg^{2+} concentration (88.2 mg kg^{-1}, 10-20cm). Tea plantations in Tea1 and pine stand had slightly poorer soil richness of exchangeable cations than tea plantations in Tea2 according to the projected position on axes 1 and 2.

I.4.5 Calculation of the chemical sub-indicator

The four chemical parameters measured in this section made significant contributions to the factors extracted by PCA (Table I.10). They were therefore used to create the chemical sub-indicator with the same method described in I.3.5 (formula I-3; Annexe, Table 4).

$$SI = \Sigma \text{ for selected variables i, j, k….n of } v i_r \times (w i \times wF1 + w i \times wF2) \quad \text{(I-3)}$$

For example:

Chemical sub-indicator of Tea1, 1

=0.16×(2506×0.70-706×0.18)+0.16×(3526×0.70-346×0.18)+0.25×(1406×0.70+8506×0.18)+0.18×(2830×0.70-402×0.18)

= 1592.18

The same calculation was made for all 20 sites. Maximum and minimum values of the raw index values were 7491.32 and 910.13. Raw values were further transformed by formula (I-2) into values between 0.1 and 1.0 for all sites (Annexe Table 4).

The orange plantation had by far the highest chemical sub-indicator while the minimum value was observed in Tea1, 2. Tea1, 2 was a site where tea trees had been planted only 3 years ago on former wasteland; it had minimum exchangeable Ca^{2+} (164 mg kg^{-1}) and Mg^{2+} (11.4 mg kg^{-1}), exchangeable K^+ was low (6.1 mg kg^{-1}) and

soil was acidic (pH=3.9). Orange plantation had highest exchangeable Ca^{2+} (2181.7 mg kg^{-1}) and K^{+} (228.6 mg kg^{-1}), exchangeable Mg^{2+} was high (68.5 mg kg^{-1}) just like pH (7.97). Tea1, 7 had highest exchangeable Mg^{2+} (50.6 mg kg^{-1}) which gave this site a higher chemical sub-indicator value than tea plantations in Tea1, that is 0.57 instead of 0.10 to 0.41. Site Tea2, 12 had the lowest chemical sub-indicator in tea plantation in Tea2 (0.26) while the other three sites had higher chemical indicator values than the Tea 1 sites, in the range of 0.34 to 0.42.

I.5 Soil organic matter (SOM) properties

I.5.1 Introduction

Biological parameters are sensitive indicators of soil quality and recognized agents of their fertility (Ruiz, 2004; Velasquez, 2004). Biological indicators often recommended include: nitrogen mineralization, microbial biomass, microbial biomass to total carbon ratio, soil respiration, respiration to microbial biomass rations, faunal populations and rates of litter decomposition (Anderson, 1994; Pankhurst *et al*., 1995; Lavalle, 1997; Sparling, 1997). It has been suggested that microbial biomass content is an integrative signal of the microbial significance in soils because it is one of the few fractions of soil organic matter that is biologically meaningful, sensitive to management or pollution and finally measurable (Powlson, 1994). Soil organic matter is a widely used indicator of soil quality as it closely relates to soil structure, and nutrient cycling. Many indicators relate to the cycling of soil organic matter, a key component of soil quality (Gregorich *et al*., 1997). Soil organic matter is important for nutrient availability, soil structure, air and water infiltration, water retention.

Near Infrared Spectrometry (NIRS) has been widely used in the assessment of the moisture content of seeds (Gera and Nottis, 1968), and more recently in measurement of C, N and P contents in plant material (Gillon *et al*., 1999) and soil properties (Velasquez *et al*., 2005; Chang *et al*., 2001) and other domains. Shepherd and Walsh (2002) developed a scheme that makes it possible to use a library of spectra of soils from eastern and southern Africa to estimate such soil properties as Ca, Mg, K and exchangeable P, organic C, pH, potential of mineralization of N, effective cation exchange capacity, and particle size and distribution, based on diffuse reflectance spectroscopy analysis. Velasquez *et al* (2005) have shown recently the great capacity of this technique to discriminate soils according to their quality, and even identify the origin of aggregates according to specific spectral signatures brought by the invertebrates, plant or other mechanisms that produced them (Velasquez *et al*., 2007).

In our study, organic matter status of soils was described through 7 parameters, i.e., microbial biomass carbon, total carbon content, total nitrogen content, ratio of microbial biomass carbon (MBC) to total carbon content, ammonium and nitrate

contents (Table I.10).

Table I.10: Parameters selected as indicators of the organic status of soils.

Soil organic matter		
1	MBC	Microbial biomass carbon (mg kg^{-1})
2	MBC/TC	Microbial biomass carbon/total carbon conten
3	Total C	Total carbon content ‰ (g kg^{-1})
4	Total N	Total nitrogen content ‰ (g kg^{-1})
5	NH_4-N	Ammonium (mg kg^{-1})
6	NO_3-N	Nitrate (mg kg^{-1})

I.5.2 Materials and methods

Soil samples for SOM analyses were taken from 0-10, 10-20 cm, and down to 20-30cm for NIRS analysis. All samples were air-dried and sieved at 2mm. One hundred gram air-dried soil samples were moistened with distilled water to 80% of their saturated water concentration, and put in closed jars. Incubations were carried out in an oven at 30℃ for 7 days. These samples were used to evaluate soil microbial biomass carbon by the chloroform fumigation-extraction method (Jenkinson, 1988). Soil NH_4-N and NO_3-N contents were measured by Nesler and phenoldisulfonic methods, respectively. For the measurement of NH_4-N, 10 g soil sample (dry weight equivalent) were shaken with 20 ml 10% KCl solution for 30 min. The solution was filtrated with Whatman GF/D after centrifugation. The NH_4^+ was measured with a spectro-colorimeter DR/700 after adding two drops of stabiliser–disperser and 0.4 ml of Nesler reagent per 0.5 ml of filtrate (method HachTM). For the measurement of NO_3-N, 10 g soil sample (dry weight equivalent) were shaken with 20 ml of 0.25% $CuSO_4$ for 30 min. After addition of 0.2 g of $Ca(OH)_2$ and $MgCO_3$ powder to the suspension, solution was filtrated. Two millilitres of filtrate were evaporated at 80℃ to dryness and then 2ml of phenoldisulfonic acid, 10 ml of distilled water and 8 ml of concentrated (28%)$NH_3 \cdot H_2O$, were added. The colour produced by phenoldisulfonic acid was also measured with a spectro-colorimeter DR/700.

I.5.3 Results and discussion

Soil organic matter variables exhibited rather large variations across the sites (Annexe, Table 5) with values of MBC from 80.4 (Tea1, 5, 0-10 cm) to 512.0 (Tea2, 12, 0-10 cm) mg kg^{-1}, ratios of MBC to total C from 0.50% (tea1, 11, 0-10 cm) to 2.76% (Tea1, 7, 10-20 cm), total C content from 7.92‰ (Tea1, 7, 10-20 cm) to 33.23‰ (Tea1, 6, 0-10 cm), total N content from 0.52‰ (Tea1, 7, 10-20 cm) to 2.85‰ (Tea1, 6, 0-10 cm), Ammonium concentration, from 28.3 (Orange, 10-20 cm) to 101.3 mg kg^{-1} (Tea1, 1, 0-10 cm) and Nitrate from 25.9 (Wasteland, 10-20 cm) to 271.5 mg kg^{-1} (Tea1, 3, 0-10 cm) .

I.5.3.1 Soil microbial biomass carbon

Tea plantations in the tea Institute (Tea1) and sugarcane, orange, pine and wasteland had much lower MBC than tea plantations and bamboo located in the same area as tea2. Sites in Tea1 did not exhibit large differences between soil samples from 0-10 and 10-20 cm, contrary to the 5 sites in Tea2 that had obvious difference between 0-10 and 10-20 cm, soil samples from surface having much higher MBC than samples from 10-20 cm. (Figure I.17).

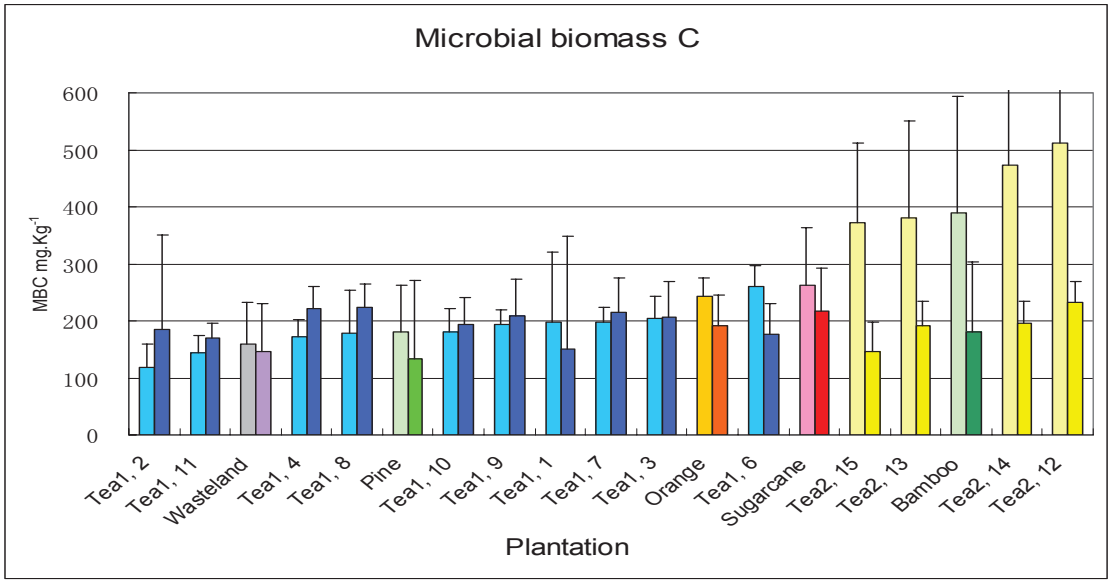


Figure I.17: Variations of microbial Biomass Carbon among the 20 sampling sites. The first columns of each site are values for soil samples taken from0-10 cm and second columns are value for soil samples taken from10-20 cm.

I.5.3.2 Total Soil carbon content

Total soil C (0-10cm) varied from 9.37‰ (Tea1, 4) to 33.23‰ (Tea1, 6) and decreased with depth (Figure I.18).

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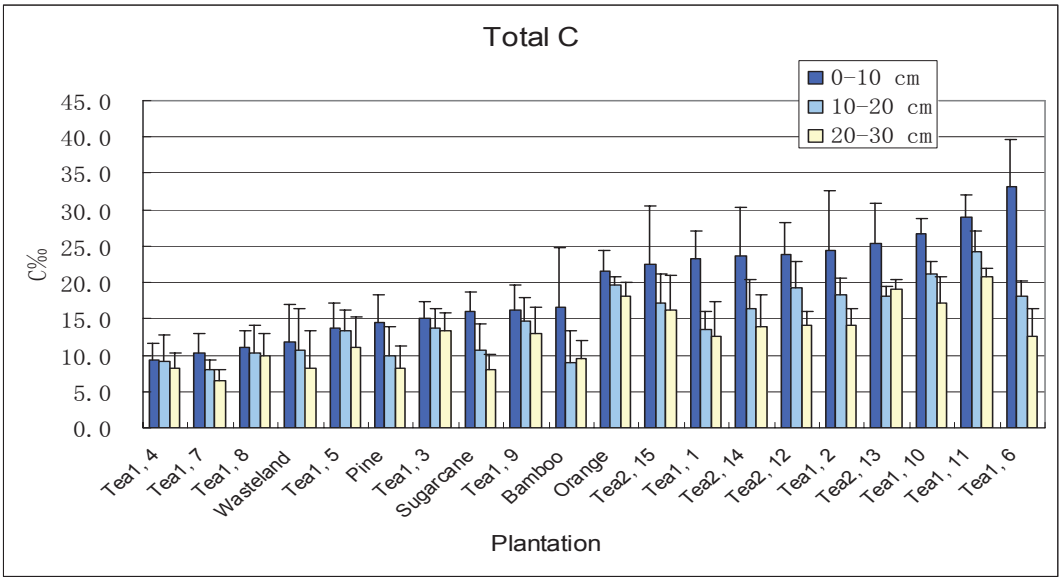


Figure I.18: Variations of total carbon content among the 20 sites. The first columns of each site are values for soil samples taken from 0-10 cm, second columns are value for soil samples taken from 10-20 cm and third column are values for soil samples taken from 20-30 cm.

Total carbon content varied largely in tea plantations of the Tea Institute (Tea1). Manure was normally applied once every 3-4 years in Tea1; the application had been done rather recently in sites Tea1, 10 and Tea1, 11 and Tea1, 2 (planted 3 years ago) when our sampling occured. Total carbon did not show large differences among the 4 tea plantations in Tea2 where manure was applied once a year.

I.5.3.3 Total soil nitrogen content

Total nitrogen content in soil taken from 0-10cm varied from 0.69‰ (Tea1, 4) to 2.85‰ (Tea1, 6) and decreased with soil depth (Figure I.19).

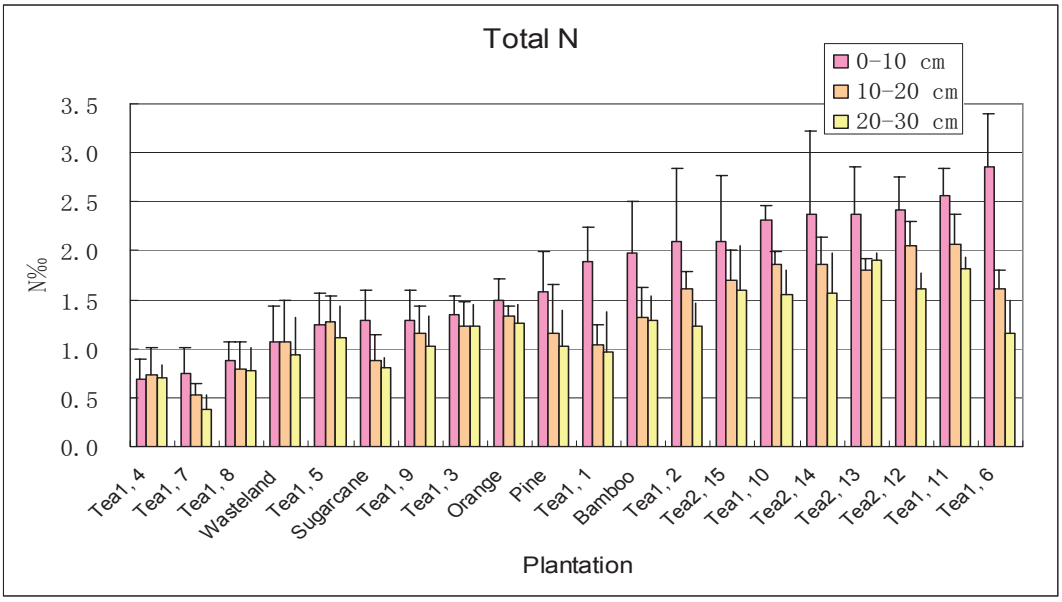


Figure I.19: Variations of nitrogen content among the 20 sites. The first columns of each site are values for soil samples taken from 0-10 cm, second columns are value for soil samples taken from 10-20 cm and third column are values for soil samples taken from 20-30 cm.

Soil nitrogen content had similar variations as total carbon content, with large variations in tea plantations in Tea1 and little differences among the 4 sites of the Tea2 plantations. Differences in manure applications likely explain this result.

I.5.3.4 Soil ammonium

Ammonium concentration in the 0-10 cm stratum varied from 37.4 (Tea1, 11) to 101.3 mg kg^{-1} (Tea1, 1)(Figure I.20).

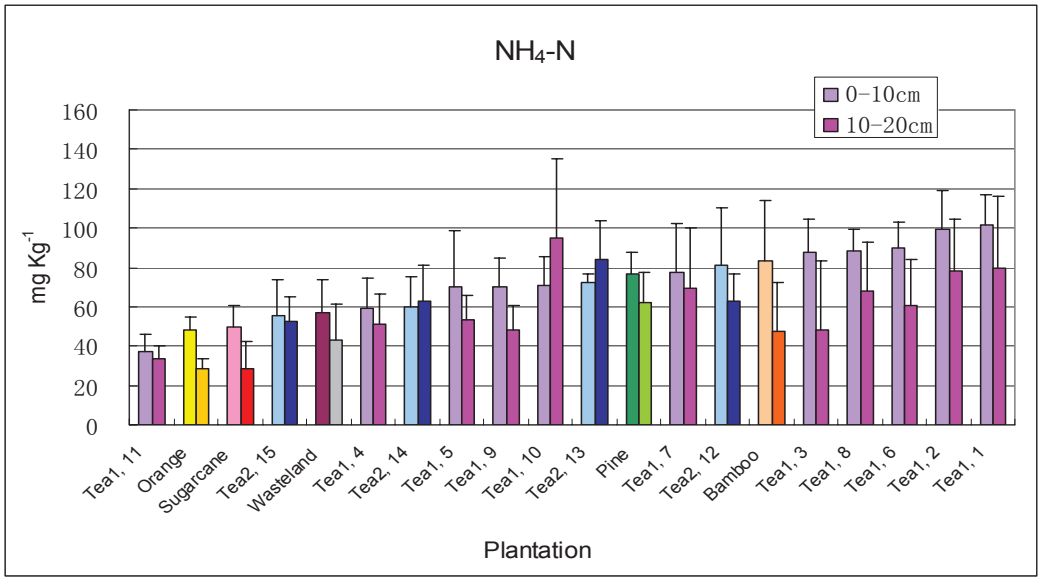


Figure I.20: Variations of soil ammonium concentration among the 20 sites. The first columns of each site are values for soil samples taken from 0-10 cm depth, second columns represent 10-20 cm depth.

Tea1, 1 and Tea1, 2 had much higher ammonium (101.3 and 99.0 mg kg^{-1}) contents in the 0-10 cm layer than sites Tea1, 11, Sugarcane and Orange (37.4, 49.9 and 48.3 mg kg^{-1} respectively).

I.5.3.5 Soil nitrate

Nitrate concentration at 0-10cm varied from 54.1 (Tea1, 4) to 271.5 mg kg^{-1} (Tea1, 3)(Figure I.21).

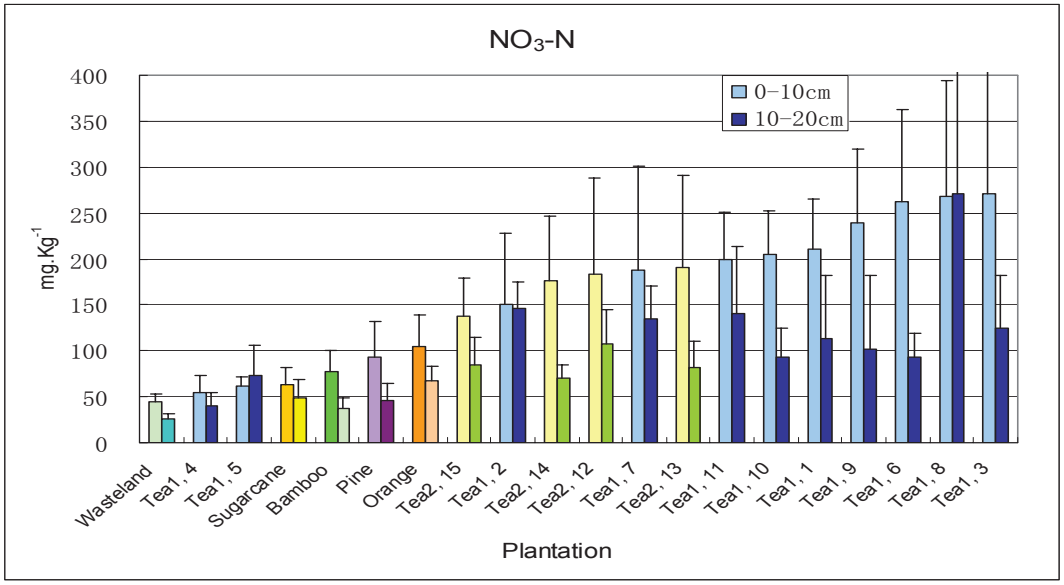


Figure I.21: Variations of soil nitrate concentration among the 20 sites. The first columns of each site are values for soil samples taken from 0-10 cm depth, second columns are values for soil samples taken from 10-20 cm.

For soil samples taken from 0-10cm, the lowest nitrate concentrations in all tea plantations were recorded in Tea1, 4 and Tea1, 5 plantations (54.1 and 61.0 mg kg^{-1} respectively). Other tea plantations has rather high concentrations comparatively, up to 150-250 mg kg^{-1} while the other five plantations had low nitrate concentrations, ranging from 43.9 mg Kg^{-1} (Wasteland) to 104.6 mg kg^{-1} (Orange).

I.5.4 Multivariate analyses (PCA) for soil organic matter parameters

Correlations among the 6 SOM parameters were computed with the ADE-4 program (Table I.11).

Table I.11: Correlation matrix of the 6 SOM parameters measured in the 20 sites (rx1000).

correlation matrix						
	MBC	MBC/TC	Total C	Total N	NH_4-N	NO_3-N
MBC	1000					
MBC/TC	636	1000				
C ‰	317	-455	1000			
N ‰	477	-282	946	1000		
$N\text{-}NH_4^+$	-41	-58	32	61	1000	
$N\text{-}NO_3^-$	77	-218	401	314	443	1000

The highest correlations were observed between C and N, while rather high positive correlations linked MBC to N, and a negative relationship was observed between the ratio of MBC/TC to total C.

The first and second principal components of PCA analysis explained 41.6% and 28.1% of the total variance respectively (Table I.12).

Table I.12: Inertia of Principal component of soil SOM parameters analysed in the 20 sites.

Inertia							
Factor	Eigenval.	Inertia%	Sum Inertias	Factor	Eigenval.	Inertia%	Sum Inertias
1	2.49E+00	0.4158	0.4158	2	1.69E+00	0.2812	0.697
3	1.24E+00	0.2075	0.9045	4	4.89E-01	0.0815	0.986
5	5.47E-02	0.0091	0.9951	6	2.95E-02	0.0049	1

Table I.13: Absolute contributions of the first two principal components of all SOM variables analysed in the 20 sites (all contributions are in 1/10000).

Variable contributions						
	MBc	MBC/TC	Total C	Total N	NH_4-N	NO_3-N
F1	470	-709	3635	3466	249	1468
F2	5029	4125	3	257	-335	-247

Factor 1 clearly separated sites according to the total carbon and nitrogen and mineral nitrogen of soil; factor 2 separated sites according to their microbial biomass carbon contents.

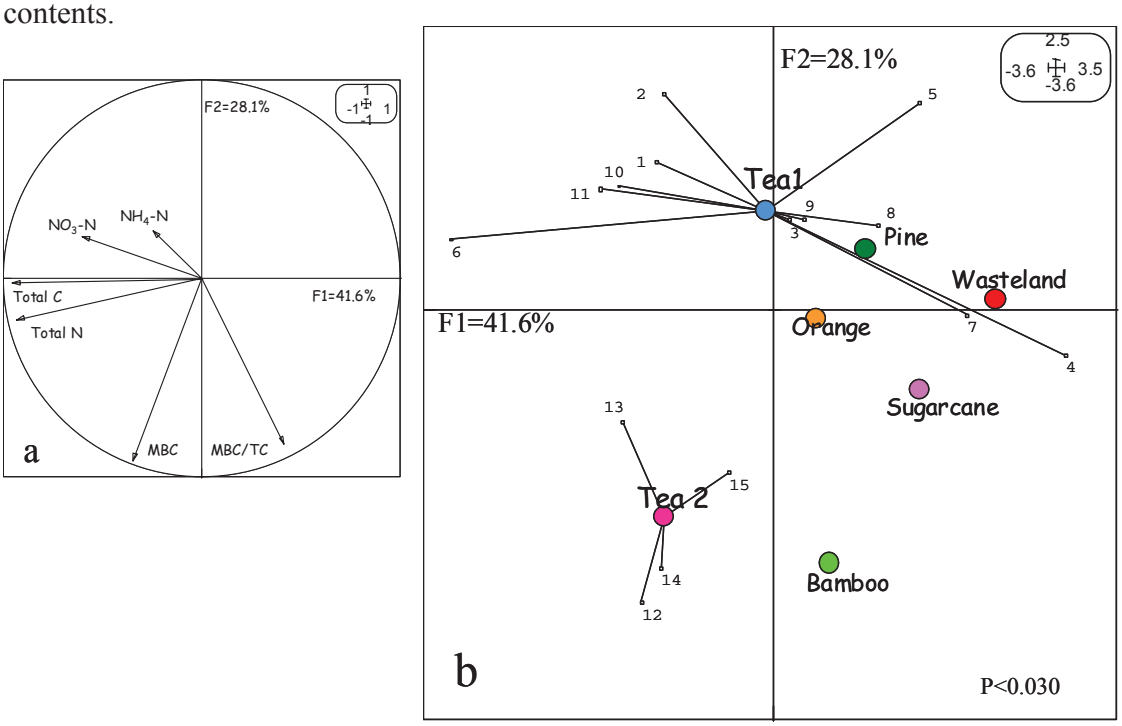


Figure I.22: Ordination of sites by PCA analysis of soil microbial biomass carbon, total carbon content, total nitrogen content, ratio of microbial biomass carbon (MBC) and total carbon content, Ammonium, Nitrate.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 6 SOM parameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together 69.7% of the inertia.

Separation of sites according to soil SOM parameters by multivariate PCA was significant ($p<0.030$). Tea plantations were separated from other plantations by factor 1, since the other five plantations had less soil carbon and available nitrogen. The projected position of plantations of the Tea1 group suggests that they had less soil carbon and nitrogen than in Tea2. Tea plantations in Tea1 were clearly separated from tea plantations in Tea2 by factor 2, as they had less microbial biomass carbon than in Tea2. Wasteland projected furthest in factor 1, had poorest soil total carbon and nitrogen condition.

I.5.5 Calculation of the soil organic matter sub-indicator

Parameters MBC, MBC/TC, total carbon and total nitrogen were the main discriminating variables according to PCA analysis (Table I.15). The SOM sub-indicators were calculated from the values of these variables, with the same method as described in I.3.5 (formula I-3; Annexe, Table 6).

$SI = \Sigma$ for selected variables i, j, k….n of $v i_r \times (w i \times wF1 + w i \times wF2)$ (I-3)

For example:

Soil organic matter sub-indicator of Tea1, 1

=0.34×(470×0.416+5029×0.281)+0.24×(-709×0.416+4125×0.281)+0.62×(3635×0.416+3×0.281)+0.60×(3466×0.416+257×0.281)

= 2615.80

The same calculation was made for all 20 sites. Maximum and minimum values of the raw index values were 4581.31 and 1176.32. Raw values were further transformed by formula (I-2) into values between 0.1 and 1.0 for all sites (Annexe, Table 6).

The highest SOM sub-indicator was found in Tea2, 12 while the minimum value was observed in Tea1, 5. Tea plantations in Tea1 had lower values of the SOM sub-indicator (all <0.60, except for Tea1, 6) than tea plantations in Tea2 (between 0.75 and 1.00) (Table I.19). Tea1, 5 was a site renewed for 2 years, applied chemical

fertilizer and manure, it had minimum microbial biomass carbon (80.4 mg kg^{-1}) and very low MBC/TC (0.57). Tea2, 12 had highest microbial biomass carbon (521.0 mg kg^{-1}) and low MBC/TC (2.20). Sugarcane and Orange plantation had similar SOM sub-indicator value (0.41 and 0.46 respectively).

I.6 Soil Macrofauna

I.6.1 Introduction

Soils host an extremely diverse community of invertebrates that differ in their adaptive strategies and hence in the functions they fulfil in soils. Macrofauna, which include invertebrates larger than 2mm, on average, comprises 16 different Orders with termites, earthworms, ants and large arthropods as the main components. Some of them have the ability to dig the soil and create specific structures for their movements and living activities (e.g. burrows, galleries, nests and chambers) plus casts and faecal pellets resulting from their feeding activities. These organisms have been called 'ecosystem engineers' for their ability to profoundly affect the soil structure and hence major soil processes via the structures that they build (Stork and Eggleton, 1992; Lavelle *et al*., 1997).

Soil macrofauna is a soil quality indicator highly responsive to soil management, especially as it modifies soil structure or organic matter dynamics (Lavelle, 1997; Linden, 1994; Ruiz, 2004; Velasquez *et al*., in press). Numerous studies highlight the way soil invertebrates can affect the biomass and activity of the microbial community, either directly through selectively feeding on fungi and bacteria, or indirectly by comminution of organic matter, dissemination of microbial propagules, and the alteration of nutrient availability (Griffiths and Bardgett, 1997).

Soil fauna populations also influence soil biological processes, nutrient cycling and soil structure and thus significantly support the provision of ecosystem services by soils (Lavelle *et al*., 2006). There is established evidence that faunal activities contribute to soil fertility since they play a large role in the transformations of soil organic matter and nutrients, at different scales of time and space, which influences their turnover and conservation, and probably improves the efficiency of the use of nutrients by plants.

Soil invertebrates should be considered as a resource that is highly sensitive to human impacts. Attention should be paid to conserve biodiversity of soil invertebrates and assess the impact of land-uses practices on their spatial distribution, at different scales, from that of a parcel to that of watershed catchment and regional and bio-geographical scales.

The link between soil structure and soil fauna has been investigated mainly in the mineral soil and for meso fauna to macro fauna. Significant effects of soil fauna on soil structure are achieved mainly by a few groups among the larger soil invertebrates that are widely distributed and generally present in large numbers. Of these groups the most important are earthworms, termites and ants (Lavelle, 1997). Many immature and mature insects, other arthropods, earthworms, nematodes and larger macro-organisms live in the soil and have an important influence on soil structure. They ingest and egest soil material, relocate plant material and form burrows (Amezketa, 1999).

There are three main reasons for examining soil macrofauna and their relationship with soil health and soil sustainability. First, recent government reports (Hamblin, 1992) have identified their potential as bioindicators of soil sustainability at the farm level, though at this stage there has been little rigorous experimentation test (Pankhurst, *et al*., 1995). Bioindicators are required to monitor changes in soil health and to provide early warning of adverse trends and identification of problem areas. Secondly, farmers need indicators of soil health which they can easily and reliably use to monitor their soil sustainability. Thirdly, farms have been slow to adopt sustainable management practices because they cannot see the benefits of the new technique and perceive a higher risk and uncertainty with them.

Over the past 5 years earthworms have been promoted as indicators of soil health by some researchers (Brown *et al*., 2000).

There is an important impediment in using biodiversity (measured simply by species richness) as an indicator of a health soil. Firstly there is a need to understand and be able to identify which species or groups of species have key functions in the maintenance of energy and material flows through an ecosystem (Silver *et al*., 1996). It has been assumed that a soil ecosystem with low biodiversity is less resilient, more vulnerable to perturbations, and ultimately not as able to function as well as a soil ecosystem with high biodiversity. However, not lots is known about the contribution of individual species or groups of species to ecosystem functioning and the effect of their removal from the soil ecosystem (Collins and Benning, 1996). Establishing who are the important macrofauna in terms of soil health requires an understanding and

quantification of their impact on the soil profile, and their association with certain soil types. Our study addressed all the parameters of soil fertility together with faunal communities. This should allow to observe significant relationships among these different attributes and ultimately to interprete which changes in soil conditions observed modifications in macrofauna communities do indicate.

Fifteen orders of soil macrofauna were found at our sites (Table I.14). As is usually done in these studies, we separated Coleoptera into adults and larvae for the very different roles the two stages use to play in soil and litter systems.

Table I.14: Soil macrofaunal orders found in the 20 sites sampled in the Yingde region.

Macrofauna		
1	Oligo	Oligochaeta
2	For	Formicidae
3	Der	Dermaptera
4	Col,a	Coleoptera,adult
5	Col,l	Coleoptera,larva
6	Isopoda	Isopoda
7	Chi	Chilopoda
8	Hem	Hemiptera
9	Ort	Orthoptera
10	Lep,l	Lepidoptera,larva
11	Spi	Spider
12	Dip	Diplopoda
13	Dip,l	Diptera,larva
14	Bla	Blattodea
15	Gas	Gastropoda
16	Isoptera	Isoptera

I.6.2 Materials and methods

Soil macrofauna was sampled with the standard TSBF (Tropical Soil Biology and Fertility) field methodology (Anderson and Ingram, 1993; Lavelle, 1998). Soil monoliths 25×25×30 cm in size were collected in four separated layers: litter, 0-10 cm, 10-20 cm, 20-30 cm for each point and hand-sorted for macrofauna in the field. Invertebrates were further identified at the order level and counted. Five monoliths were sampled at each site.

I.6.3 Results and discussion

Soil macrofauna density exhibited rather large variations across the orders and sites *(*Annexe Table 7; Figure I.23*)*

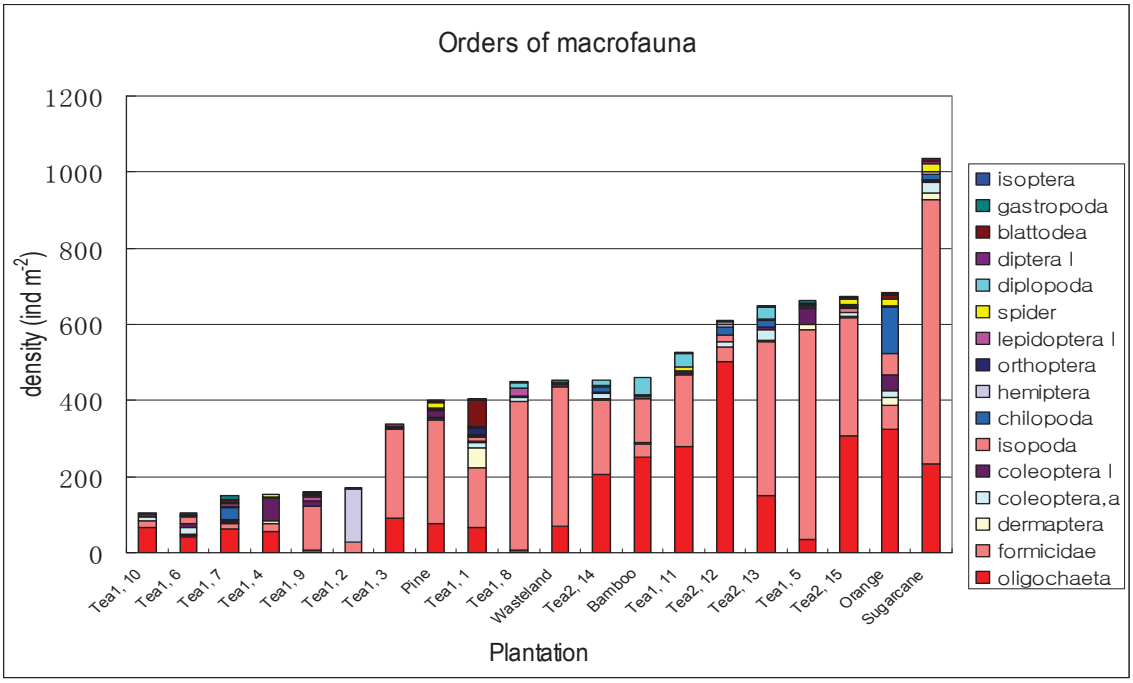


Figure I.23: Variations of soil macrofauna density and composition among the 20 sites (mean values of 5 points).

Macroinvertebrate communities comprised 432.6 ind m^{-2} on average, with a clear dominance of ants (204.6 ind m^{-2}) and earthworms (141.6 ind m^{-2}).

In all the 20 sites, Sugarcane had the highest macrofauna density (1036.8 ind m^{-2}) and Tea1, 6 and Tea1, 10, had the lowest macrofauna density (105.6 ind m^{-2}). Sites Tea2, 12, 13, 15, Tea1, 5, and orange had macrofauna density between 600 to 800 ind m^{-2}, and tea plantations Tea1, 10, 6, 7, 4, 9, 2 in Tea1 had much lower macrofauna density less than 200 ind m^{-2}.

Site Tea2, 12 had the highest density of earthworm (502.4 ind m^{-2}), while the Orange plantation, Tea 2, 15, Tea1 11, Bamboo forest, Sugarcane crop and Tea2, 14 also had high earthworm density of more than 200 ind m^{-2}. Tea plantations Tea2 had more macrofauna density compared with tea plantations in Tea1.

I.6.4 Multivariate analyses (PCA) for soil macrofauna

The Correlations among the 16 groups of soil macrofauna were computed with the ADE-4 program (Table I.15).

Table I.15: Correlation matrix of the 16 orders of soil macrofauna measured in the 20 sites (rx1000).

correlation matrix	Oligo	For	Der	Col,a	Col,l	Isopoda	Chi	Hem	Ort	Lep,l	Spi	Dip	Dip,l	Bla	Gas	Isoptera
Oligo	1000															
For	-33	1000														
Der	-17	141	1000													
Col,a	360	323	267	1000												
Col,l	-178	-49	247	-188	1000											
Isopoda	418	-311	54	23	22	1000										
Chi	418	-159	280	290	328	390	1000									
Hem	-207	-198	-115	-173	-197	-112	-106	1000								
Ort	-148	76	903	11	145	-4	45	-90	1000							
Lep,l	-371	9	-139	-193	-212	-213	-148	7	-75	1000						
Spi	358	299	244	275	225	137	357	-182	-32	-247	1000					
Dip	331	-24	-298	133	-328	480	-77	-146	-255	17	-113	1000				
Dip,l	-13	494	28	200	-131	-166	-84	-88	-63	-81	463	-260	1000			
Bla	-90	-23	909	129	-34	8	70	-68	904	6	11	-218	-72	1000		
Gas	-27	64	199	-187	146	-60	421	-198	206	194	-180	-76	-302	198	1000	
Isoptera	315	-168	303	184	420	375	948	-67	109	-128	415	-151	-101	71	323	1000

Blattodea had positive correlations with Dermaptera and Orthoptera, Isoptera had significant positive correlations with chilopoda.

The first three components explained 54% of total variance together, with respective values of 22.2%, 17.6% and 14,3% for F1, F2 and F3 (Table I.16).

Table I.16: Inertia of Principal component soil macrofauna measured in the 20 sites.

Inertia							
Factor	Eigenval.	Inertia%	Sum Inertias	Factor	Eigenval.	Inertia%	Sum Inertias
1	3.55E+00	0.2217	0.2217	2	2.81E+00	0.1758	0.3974
3	2.29E+00	0.1429	0.5403	4	1.76E+00	0.1102	0.6504
5	1.36E+00	0.0848	0.7352	6	1.06E+00	0.0665	0.8017
7	8.16E-01	0.051	0.8527	8	6.62E-01	0.0414	0.8941
9	6.04E-01	0.0378	0.9319	10	4.45E-01	0.0278	0.9596
11	2.51E-01	0.0157	0.9753	12	1.86E-01	0.0116	0.9869
13	1.52E-01	0.0095	0.9964	14	4.09E-02	0.0026	0.999
15	1.19E-02	0.0007	0.9997	16	4.10E-03	0.0003	1

Table I.17: Absolute contributions of the first two principal components of 16 orders of soil macrofauna analysed in the 20 sites (all contributions are in 1/10000).

Variable contributions																
	Oligo	For	Der	Col,a	Col,l	Isopoda	Chi	Hem	Ort	Lep,l	Spi	Dip	Dip,l	Bla	Gas	Isoptera
F1	279	5	1874	313	486	261	1539	-204	1084	-245	623	-151	1	1041	325	1562
F2	1673	-65	-884	245	-3	1086	742	-61	-1583	-304	437	855	1	-1415	-89	551

Factor 1 separates sites according to the overall density of most groups, with special importance of the litter dwellers Dermaptera, Blattodea, Orthoptera, Isoptera, and Chilopoda; factor 2 separated opposed sites with large densities of Oligochaeta, Isopoda, Diplopoda to sites with large densities of Blattodea and Orthoptera.

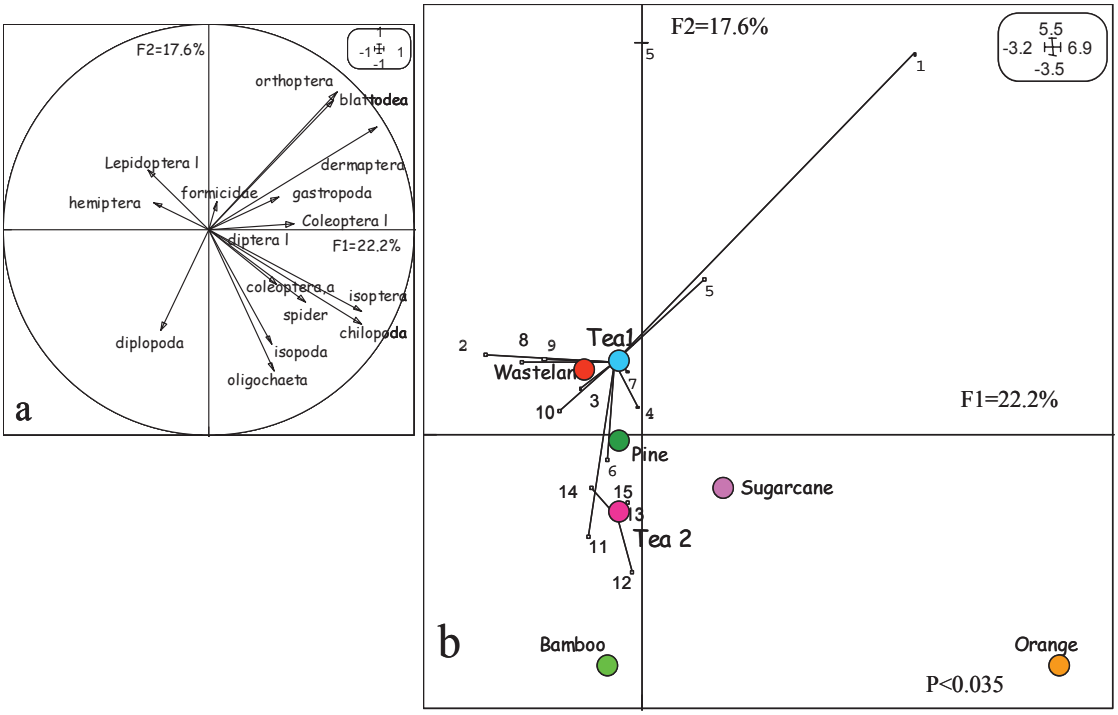


Figure I.24: Ordination of sites by PCA analysis of soil 16 orders of soil macrofauna.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 16 orders of soil macrofauna.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together 39.8% of the inertia.

Separation of site groups according to the soil macrofauna by multivariate PCA was significant ($p<0.035$). According to soil macrofauna, the orange plantation and Tea1, 1 were far separated from other sites along axis 1; they were the sites with largest diversities of macrofauna, especially with dense and diverse communities of litter dewelling invertebrates. Factor 2 opposed Bamboo and orange plantations to Tea1, 1 and more generally, Tea 1 sites with relatively low densities of Oligochaeta, Isopoda and Diplopoda from Tea 2 that had more.

I.6.5 Calculation of the soil macrofauna sub-indicator

Multivariate PCA analysis allowed identify the main factors that explain changes in macroinvertebrate communities, and quantify their respective inertias. Eight orders (Oligochaeta, Dermaptera, Iospoda, Chilopoda, Orthoptera, Diplopoda, Blattodea, Isoptera) were most responsive to these changes (Table I.20). The soil macrofauna sub-indicators were calculated with the same method described in I.3.5 (formula I-3; Annexe, Table 8).

$$SI = \Sigma \text{ for selected variables i, j, k....n of } vi_r \times (wi \times wF1 + wi \times wF2) \quad \text{(I-3)}$$

For example:

Soil macrofauna sub-indicator of Tea1, 1= 0.22×(279×0.22+1673×0.18) + 1.00×(1874×0.22-884×0.18)+0.18×(261×0.22+1086×0.18)+0.12×(1539×0.22+742×0.18)+1.00×(1084×0.22-1583×0.18)+0.10×(-151×0.22+855×0.18)+1.00×(1041×0.22-1415×0.18) + 0.10×(1562×0.22+551×0.18)

=441.40

The same calculation was made for all 20 sites. Maximum and minimum values of the raw index values were 1417.32 and 184.30. Raw values were further transformed by formula (I-2) into values between 0.1 and 1.0 for all sites (Annexe, Table 8).

The orange plantation had by far the highest macrofauna sub-indicator while the minimum value was observed in Tea1, 2. Most all of the soil macrofauna sub-indicator is less than 0.50, except for orange plantation.

In all the 20 sites, Sugarcane had the highest macrofauna density (1036.8 ind m^{-2}) but with 694.4 ind m^{-2} of formicidae which was wiped off because absolute contribution was less than half of maximum. Orange had the second highest macrofauna density (684.8 ind m^{-2}) with very high density of Oligochaeta (323.2 ind m^{-2}) and Chilopoda (124.8 ind m^{-2}), these two orders were main characteristic. The biodiversity of orange plantation was much higher than other sites too, it had all together 12 orders of macrofauna and seven of them were most responsive to changes in macroinvertebrate communities. It made Orange had much higher soil

macreofauna sub-indicator than others.

Sites Tea2, 12 and Bamboo had high macrofauna density (611.2 and 460.8 ind m^{-2}) and high density of oligochaeta (502.4 and 252.8 ind m^{-2}).

Tea plantations in Tea2 had higher soil macrofauna sub-indicator than tea plantations in Tea1. There was no big difference between tea plantations in tea1 (varied from 0.10 to 0.29).

I.7 Soil morphology

I.7.1 Introduction

Structure is a key factor in the functioning of soil, its ability to support plant and animal life, and mitigate environmental problems with particular emphasis on soil carbon (C) sequestration and water infiltration and storage.

The decline in soil structure is increasingly seen as a form of soil degradation (Chan *et al*., 2003) and is often related to land use and soil/crop management practices. Soil structure influences soil water movement and retention, erosion, crusting, nutrient recycling, root penetration and crop yield.

Soil structure refers to the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development (Lal, 1991). Favorable soil structure and high aggregate stability are important to improving soil fertility, increasing agronomic productivity, enhancing porosity and decreasing erodibility.

Soil aggregation in our treatments was assessed by a visual method derived from the Topoliantz *et al* (2000) "small volume" approach and validated across a wide range of sites in Nicaragua, Colombia, France, Brazil, Guyana (Velasquez, 2004; Velasquez *et al*, 2006).

In this study, 11 items were studied as soil morphological properties (Table I. 18).

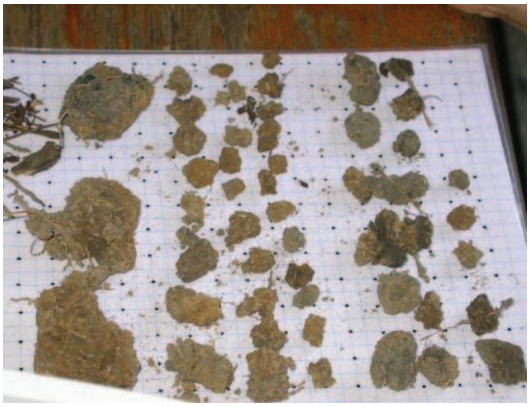
Table I.18: The 11 items used to assess soil morphology (after Velasquez et al., 2006).

BA l	Large biogenic aggregate
BA m	Medium biogenic aggregate
BA s	Small biogenic aggregate
PA l	Large physical aggregate
PA m	Medium physical aggregate
PA s	Small physical aggregate
Roots	Roots
Stones	Stones
Woods	Woods
Stems	Stems
Seeds	Seeds

I.7.2 Method of soil morphology assessment

A soil monolith 5×5×5 cm in size was taken for morphology analysis in the centre of the sampling area of each site (Photo I.1; Photo I.2). Each monolith was manually separated into component macro-aggregates and visible solid features from a few mm to several cm.

Photo I.1: Taking soil samples from field for morphology analysis (from Velasquez).



Biogenic and physical
Aggregates of different sizes

Other soil items

Photo I.2: Visually separated soil macroaggregates with different sizes and other items (from Velasquez).

Aggregates were further classified as "biogenic" clearly produced by macroinvertebrates and physical aggregates produced by physical processes then classified according to their shape, size (small: d < 1 cm; medium size: 1 cm < d < 3 cm; large: d > 3 cm) and colour. Remaining items were separated at the same time (Velasquez, 2004; Velasquez *et al*, 2006).

(1) Biogenic aggregates

Biogenic macroaggregates are produced by macro-invertebrates (mainly earthworms and termites, together with coleopteran larvae and diplopoda). These aggregates generally have round shapes and darker color than other aggregates. Earthworm casts generally comprise embedded round and concave structures corresponding to successive defecations of soil material into the galleries and macropores that they have previously created. Other macro-aggregates are classified as biogenic whenever galleries, fabrics or dejections of large invertebrates are visible on at least one side of the aggregate. Termites, ants and coleoptera are the most frequent producers of such structures.

(2) Physical aggregates

This kind of macroaggregates is produced by such physical processes as drying

and wetting, or freeze/thaw alternations.

(3) Remaining items

Roots, seeds, leaf debris, stems and woods debris, invertebrates, seeds and stones comprised the other categories of items are separated from the block.

Separated items were quantified using a grid enumeration technique. Aggregates of a given category were displayed over a grid of 0.5×0.5 cm square units and the total surface covered was measured. Root lengths or absolute numbers of e.g., gravels or invertebrates were also used as measurements. This simple way of assessing the different units allows making measurements in field conditions, when no precision balance or energy is available. An alternative to this relative assessment may be given by weighing items of each class after drying to constant weight.

I.7.3 Results and discussion

Soil morphological items exhibited large variations across the 20 sites (Annexe, Table 9; Figure I.25).

Tea plantation Tea1, 11 in tea institute (Tea1) had the largest amount of large biogenic aggregates (BA l) (37 units), pine forest had most medium sizes BA (256 unites) and tea plantation Tea2, 15 in Shangmingxuan tea garden (Tea2) had the largest number of small BA (202 unites). Physical aggregates had highest values in Tea1, 3; Tea2, 14 and Tea1, 10 with respective values of 31, 68 and 138 unites for large, medium sized and small aggregates. Bamboo forest had the highest amount of roots. Highest amounts of stones, wood pieces and seeds were found in wasteland, Tea2, 15, Tea1, 11 and orange plantation respectively.

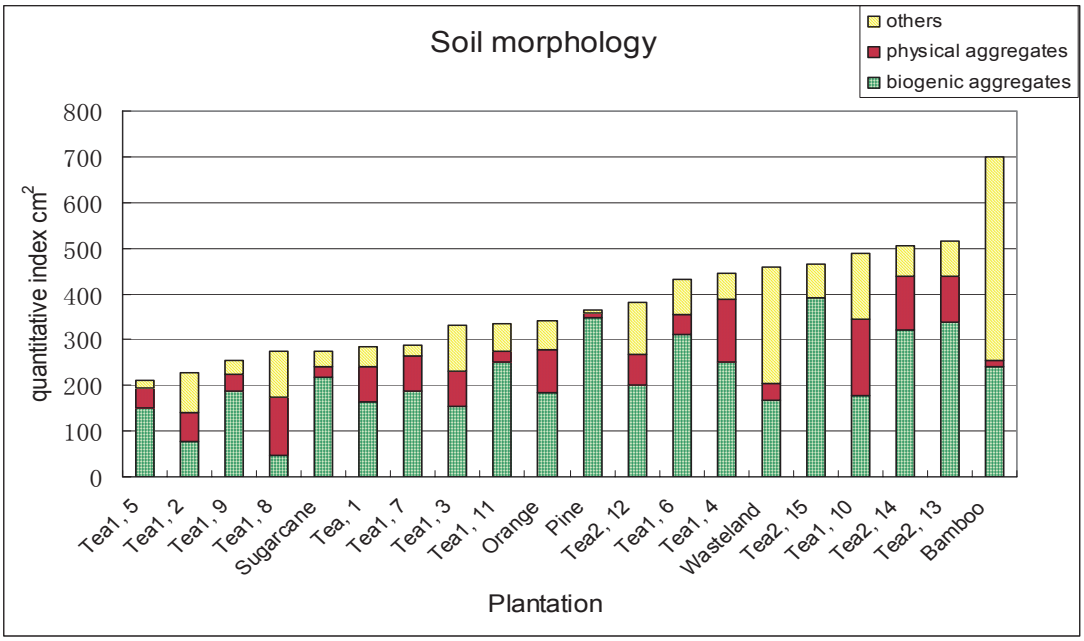


Figure I.25: Variations of soil morphological composition among the 20 sites.

Plantation of Pine, Tea2, 15, Sugarcane, Tea1, 11, 9, 6, 5 had absolute proportions of biogenic aggregates value (amount of biogenic aggregates / amount of all the 11 morphological items) higher than 70%.

I.7.4 Multivariate analyses (PCA) for soil morphology

The first two factors of the analysis explained respectively 21.78 and 17.05% of variance. The next three factors explained together another 37.82% thus showing that discrimation of sites according to soil morphology is done by a diversity of factors. (Table I.19).

Table I.19: Inertia of Principal component of 11 soil morphological items studied in the 20 sites.

Inertia

Factor	Eigenval.	Inertia%	Sum Inertias	Factor	Eigenval.	Inertia%	Sum Inertias
1	2.40E+00	0.2178	0.2178	2	1.88E+00	0.1705	0.3884
3	1.51E+00	0.1371	0.5255	4	1.43E+00	0.1299	0.6554
5	1.23E+00	0.1119	0.7673	6	9.42E-01	0.0856	0.8529
7	6.02E-01	0.0547	0.9076	8	4.19E-01	0.038	0.9457
9	2.90E-01	0.0264	0.972	10	1.80E-01	0.0164	0.9884
11	1.28E-01	0.0116	1				

Table I.20: Absolute contributions of 11 soil morphological items studied in the 20 sites to the first two principal components (all contributions are in 1/10000).

Variable contributions

	BA l	BA m	BA s	PA l	PA m	PA s	Roots	Stones	Woods	Stems	Seeds
F1	669	188	2422	-217	-1414	-1036	-35	-486	2155	1406	8
F2	1214	38	-123	2262	951	254	-1929	-1755	30	109	1329

First factor opposed soils with small biogenic aggregates and wood debris to soils with predominantly physical aggregates; factor 2 opposed soils with large amounts of physical and biogenic aggregates to soils with large amounts of stones and roots (Figure I.26).

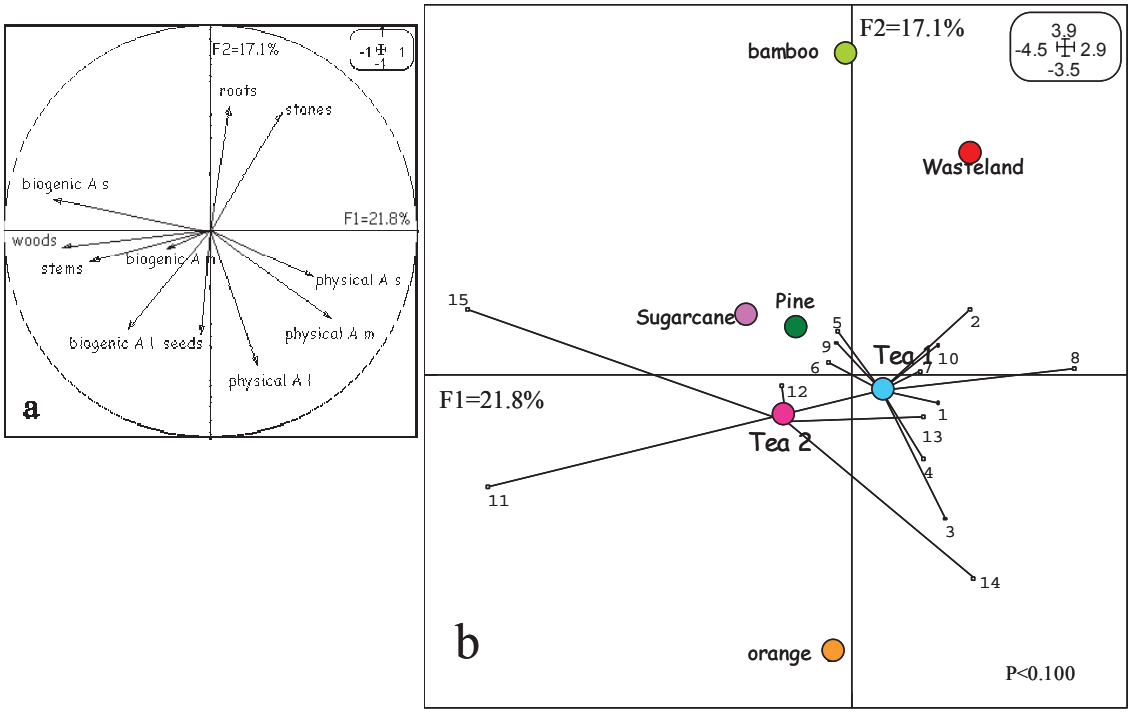


Figure I.26: Ordination of sites by PCA analysis of soil morphological items.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 11 soil morphological items.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
Factors 1 and 2 explain together 38.9% of the inertia.

Factor 1 separated wasteland and tea plantations in the Tea Institute area (Tea1) from other sites. Factor 2 separated Orange, tea plantations in Tea1 and Tea2 from the other 4 plantations. Orange and Bamboo plantation projected far in factor 2 in different direction, Orange had the most seed number (41) and bamboo had most roots (280). Tea1, 11 and tea2, 15 projected far in factor 1, they had most large and small biogenic aggregates (37 and 202). Site separation according to soil morphology however was only significant at the 10% threshold ($p<0.100$).

I.7.5 Calculation of the soil morphology sub-indicator

Evaluations of contributions of the different morphological variables by PCA items in the 20 sites indicated 9 of them that were most important i.e., large and small biogenic aggregates, large and medium physical aggregates, roots, stones, woods,

stems and seeds) (Table I.20). The soil morphology sub-indicators were calculated with the same method described in I.3.5 (formula I-3; Annexe, Table 10).

SI = Σ for selected variables i, j, k….n of $v i_r \times (w i \times wF1 + w i \times wF2)$ (I-3)

For example:

Soil morphology sub-indicator of Tea1, 1= 0.42×(669×0.22+1214×0.17) + 0.26×(2422×0.22-123×0.17)+1.00×(-217×0.22+2262×0.17)+0.54×(-1414×0.22+951×0.17)+0.19×(-35×0.22-1929×0.17)+0.17×(-486×0.22-1755×0.17)+0.10×(2155×0.22+30×0.17) + 0.10×(1406×0.22+109×0.17) + 0.10×(8×0.22+1329×0.17) =508.30

The same calculation was made for all 20 sites. Maximum and minimum values of the raw index values were 1341.78 and –5.65. Raw values were further transformed by formula (I-2) into values between 0.1 and 1.0 for all sites (Annexe, Table 10).

The highest soil morphology sub-indicator was found in Tea1, 11 while the minimum value was observed in Wasteland.

Tea1, 11 and Tea2, 15 had the highest morphology sub indicator, which had the highest proportions of large (37 unites) and small biogenic aggregates (202 unites) respectively. The two sites had relatively high soil macrofauna sub-indicator (0.31 and 0.32).

Wasteland with few biogenic and physical aggregates and a large number of stones, had the lowest value of the morphological sub indicator. Five sites: Tea1, 6, 7, Tea2, 13, Tea1, 9, 5, had intermediate and similar values of the soil morphology sub-indicator, from 0.46 to 0.48.

I.8 General indicator of soil quality (GSQI)

I.8.1 Multivariate analyses (PCA) for sub-indicator

Values of the five different sub indicators of soil quality are grouped and compared in table I.21.

Table I.21: Chemical, physical, organic matter, macrofauna and soil morphology sub-indicators.

Plantation	Physical	Chemical	SOM	Macrofauna	Morphology
Tea1, 1	0.19	0.19	0.48	0.29	0.44
Tea1, 2	0.60	0.10	0.43	0.10	0.28
Tea1, 3	0.36	0.28	0.33	0.14	0.21
Tea1, 4	0.65	0.41	0.18	0.15	0.50
Tea1, 5	0.80	0.35	0.10	0.16	0.48
Tea1, 6	0.68	0.20	0.85	0.16	0.46
Tea1, 7	0.25	0.57	0.22	0.23	0.48
Tea1, 8	0.10	0.30	0.20	0.14	0.30
Tea1, 9	0.35	0.29	0.31	0.11	0.48
Tea1, 10	0.46	0.27	0.57	0.13	0.51
Tea1, 11	0.36	0.29	0.60	0.29	1.00
Tea2, 12	0.61	0.26	1.00	0.43	0.62
Tea2, 13	0.72	0.42	0.82	0.28	0.48
Tea2, 14	0.34	0.34	0.93	0.27	0.38
Tea2, 15	0.63	0.42	0.75	0.29	0.94
Sugarcane	0.93	0.38	0.41	0.31	0.56
Orange	1.00	1.00	0.46	1.00	0.63
Pine	0.57	0.31	0.32	0.16	0.43
Bamboo	0.54	0.44	0.74	0.48	0.15
Wasteland	0.55	0.46	0.21	0.14	0.10

Interestingly, sites that have low ranking in certain types of quality not necessarily have them in all categories. For example, Tea1, 12 that has the lowest

values for Chemical and Macrofauna sub indicators has a fairly good physical sub indicator value. On the opposite, the orange plantation that has the maximum possible markings for physical, chemical and morphological indicators, has much smaller values for the other two sub indicators.

Correlations among the 5 group sub-indicators computed with the ADE-4 program however showed only one significant correlations among chemical and macrofauna indicators (Table I.22).

Table I.22: Correlation matrix of the 5 sub-indicators in the 20 sites (rx1000).

	Physical	Chemical	SOM	Macrofauna	Morphology
Physical	1000				
Chemical	430	1000			
SOM	114	-124	1000		
Macrofauna	460	781	296	1000	
Morphology	203	139	280	263	1000

Soil chemical sub-indicator had a significant positive correlation with macrofauna sub-indicator.

A PCA analysis was performed with the matrix of sub indicator values. The first and second principal components explained 45.6% and 24.6% of the total variance respectively (Table I.23).

Table I.23: Inertia of Principal component of the 5 sub-indicators in the 20 sites.

Inertia							
Factor	Eigenval.	Inertia%	Sum Inertias	Factor	Eigenval.	Inertia%	Sum Inertias
1	2.2776E+00	0.4555	0.4555	2	1.2306E+00	0.2461	0.7016
3	7.3064E-01	0.1461	0.8478	4	6.4376E-01	0.1288	0.9765
5	1.1742E-01	0.0235	1.0000				

Table I.24: Absolute contributions of the first two principal components of the 5 sub-indicators at the 20 sites (all contributions are in 1/10000).

Variable contributions					
	Physical	Chemical	SOM	Macrofauna	Morphology
Factor 1	2157	2914	378	3651	897
Factor 2	-63	-1782	5494	-29	2629

Factor 1 ordinated sites according to values of all indicators, with higher contribution of macrofauna, chemical and physical sub indicators. The orange plantation had by far the largest coordinate on this axis while largely negative values occurred in several sites of the Tea1 group.

Factor 2 separated soils with high values of the soil organic matter and morphology sub indicators, and low values of the chemical one (Tea2 and part of Tea1 sites). Separation of sites according to the 5 sub-indicators was significant ($p<0.001$).

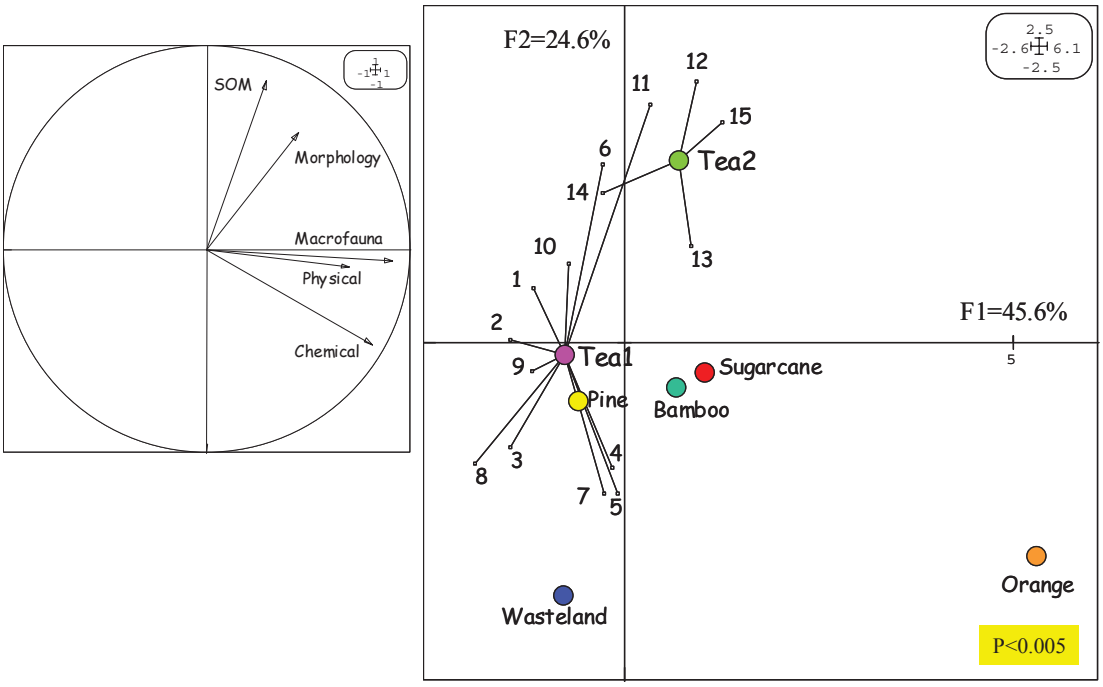


Figure I.27: Ordination of sites by PCA analysis of chemical, physical, soil organic matter, soil macrofauna and soil morphology sub-indicators.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 5 sub-indicators.
(b) Projection of sites in the plane defined by factors 1 and 2. Small circles indicate

barycenters related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together70.2% of the inertia.

I.8.2 Calculation of the general indicator of soil quality

Multivariate analysis of the matrix of the five sub-indicators provided absolute contributions to factors extracted by PCA *(*Table I.24*)* and inertia of factor 1 and factor 2 (Table I.23). These parameters were further used to create the sub-indicator coefficient with formula I-4.

Coefficient (F) = absolute contribution of sub-indicator to factor1× inertia explained by factor 1 + absolute contribution of sub-indicator to factor 2× inertia explained by factor 2 (I-4)

For example,

Coefficient for chemical sub-indictor = 0.2914 × 0.456 + (-0.1782) × 0.246 = 0.089

The same calculation was made for the five sub-indicators, to make calculating general soil quality indicator easier, we multiply the gotten coefficient by 10 (Table I. 25).

Table I.25: *Coefficients of the five sub-indicators.*

	Physical	Chemical	SOM	Macrofauna	Morphology
Coefficient	0.97	0.89	1.52	1.66	1.06

General indicator of soil quality was determined by the coefficient of each sub-indicator and the sub-indicator values (formula I-5).

General indicator $= \sum_{C,P,S,F,M}$ (reduced value of sub-indicator × coefficient) (I-5)

C, P, S, F, M are chemical, physical, soil organic matter, macrofauna and morphology sub-indicator (Table I.21).

For example:

General indicator of soil quality of Tea1, 1 = 0.97 × 0.19 + 0.89 × 0.19 +1.52 × 0.48 + 1.66 × 0.29 + 1.06 × 0.44 = 2.04

The same calculation was made for the 20 sites, maximum and minimum values of the raw index values were 4.89 and 1.21. Raw values were further reduced by formula (I-2) into values between 0.1 and 1.0 for all sites (Table I.26).

Table I.26: General indicator of soil quality (GSQI) of the 20 sites.

Plantation	GSQI	Reduced GSQI
Tea1, 8	1.21	0.10
Tea1, 3	1.56	0.19
Wasteland	1.60	0.20
Tea1, 9	1.76	0.23
Tea1, 2	1.79	0.24
Tea1, 7	1.97	0.29
Tea1, 5	2.02	0.30
Tea1, 1	2.04	0.30
Pine	2.04	0.30
Tea1, 4	2.05	0.31
Tea1, 10	2.32	0.37
Tea2, 14	2.88	0.51
Tea1, 6	2.88	0.51
Sugarcane	2.96	0.53
Bamboo	3.01	0.54
Tea1, 11	3.07	0.55
Tea2, 13	3.30	0.61
Tea2, 15	3.59	0.68
Tea2, 12	3.71	0.71
Orange	4.89	1.00

The highest general indicator of soil quality was found in orange plantation while the minimum value was observed in tea plantation Tea1, 8. Tea plantations in Shangmingxuan tea garden (Tea2) had higher general indicator of soil quality than tea plantations in tea Institute (Tea1) except for Tea1, 11.

I.9 Ability of IGQS to assess changes occurred after soil restoration

The general indicator of soil quality and its 5 sub-indicators have clearly ordinated different types of plantations with different history and managements according to soil quality criteria.

It is obvious that no isolated property can provide a comprehensive picture of the quality of a specific soil and the combination of five indicators assessing different aspexcts of soil quality resulted to be very efficient.

An opportunity was given to test our own indicator, calibrated for agroecosystems of the Yingde region, in an experiment of soil restoration. This situation where clear effects of the restoration technique have been observed (Nuria Ruiz, Elena Velasquez, Dai Jun, Patrick Lavelle *et al*., unp. data), would allow to see how sensitive were our indicators.

I.9.1 The (FBO) fertilisation Bio-Organic technology

The FBO technology was invented in the early 90's by Professor Bikram Senapati and his research team of Sambalpur University (Orissa, India) as part of an European Community project (MACROFAUNA, TS3*0292 EDB. (1992-1995) lead by Professor Patrick Lavelle (University of Paris VI /IRD). The objective of the project was to develop management options using earthworms as a resource in tropical agricultural systems.

FBO restores soil function by creating small highlands with full ecological functionality in a soil that has been significantly degraded. Plants will then send their roots in these places and get the nutrients and growth stimulating factors that they need. Once improved their vigor and productivity, increased litter production will allow soil restoration to expand from the islands to the whole plot. The islands are trenches 1.5m in length, 30cm wide and 45 cm deep, filled with soil and two sorts of organic matter of contrasted qualities and inoculated with earthworms. The choice of earthworms and organic matters and their specific spatial array are key elements for the success of the technology (Senapati *et al*., 1999).

The FBO technology was applied at our study sites, in three blocks of the tea

Institute at Yingde that had been previously evaluated (Tea1, 7; Tea1, 8;Tea1, 9) with respective GOSQ values of 0.31, 0.10 and 0.18. Four different treatments were installed.

T1: 100% FBO technology: after application of the FBO technology, fertilisation is fully organic and in case of severe insect attacks, only bio-pesticides are used.

T2: 50% FBO, bio-pesticides: application of FBO and fertilisation half chemical, half organic. Use bio-pesticides if necessary.

T3: 50% FBO, chemical pesticides.

T4: Conventional treatment. This control soil receives the same amount of nutrient application as the other three treatments, as chemical inputs. Chemical pesticides are used when necessary.

Trenches were dug between tea rows. Inorganic and organic inputs were used as well as several local earthworm species. Sampling was done in March and October 2005, 6 soil samples for chemical, physical and SOM analysis were taken each time for each block, three inside and three outside the trenches in each treatment. Soil macrofauna was assessed using TSBF technology (Lavelle, 1988; Anderson and Ingram, 1993), 6 soil morphology samples were taken at the surface of soil for each treatment.

In the present chapter, we only present results of the 100% FBO treatment (T1) and the control (T4) treatment for comparison.

I.9.2 Soil sub-indicators calculation

Assessments were done 6 months (March 2005) and 12 months (October 2005), after the installation of the experiment. The same analyses and data treatments as the ones exposes in the earlier sections of this chapter were done.

The FBO technology induced rather significant changes in soil macrofauna and morphology (Figure I.28).

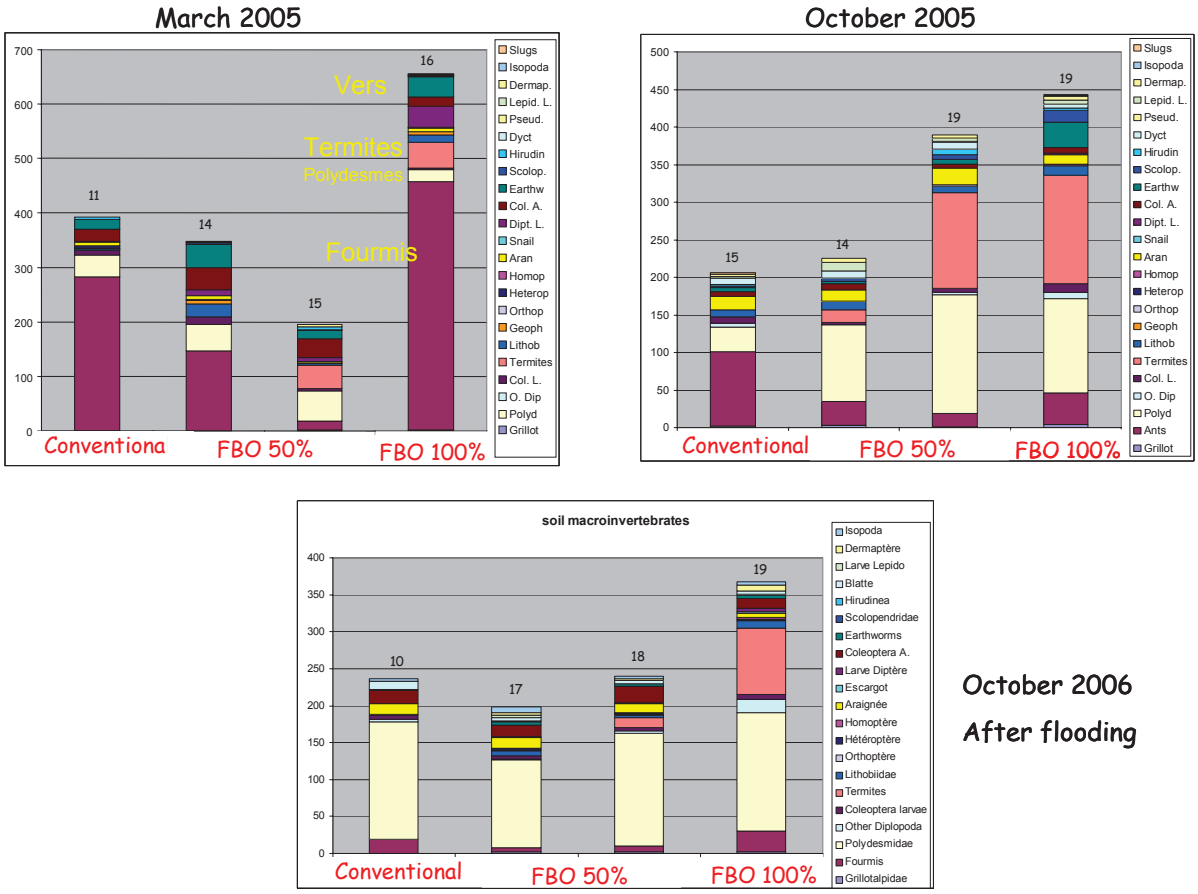


Figure I.28: Effect of application of the FBO technology on soil macroinvertebrate communities (bars are average of densities m² of invertebrates extracted from three 25x25x30cm monoliths, in three replicated plots per treatment). Numbers on top of columns indicate richness in different order of macrofauna (data Nuria Ruiz).

FBO soon had more numerous macrofauna communities than the conventional system, due to rather massive organic inputs. Changes in the composition of communities also occurred. Ants that were over dominant before the experiment became much less important in FBO treatment, while termites, polydesmidae, Coleoptera and earthworms increased significantly. In October 2006, flooding occurred during several weeks and this seems to have had significant effects on communities in all treatments.

A PCA analysis performed on this set of data clearly ordinated the four treatments from conventional, with the highest values along axis 1 to 50% and 100%

FBO treatments. Axis 2 separated the islands of high fertility (“inside”) from teh surrounding non treated soil (“outside”) (Figure I. 29).

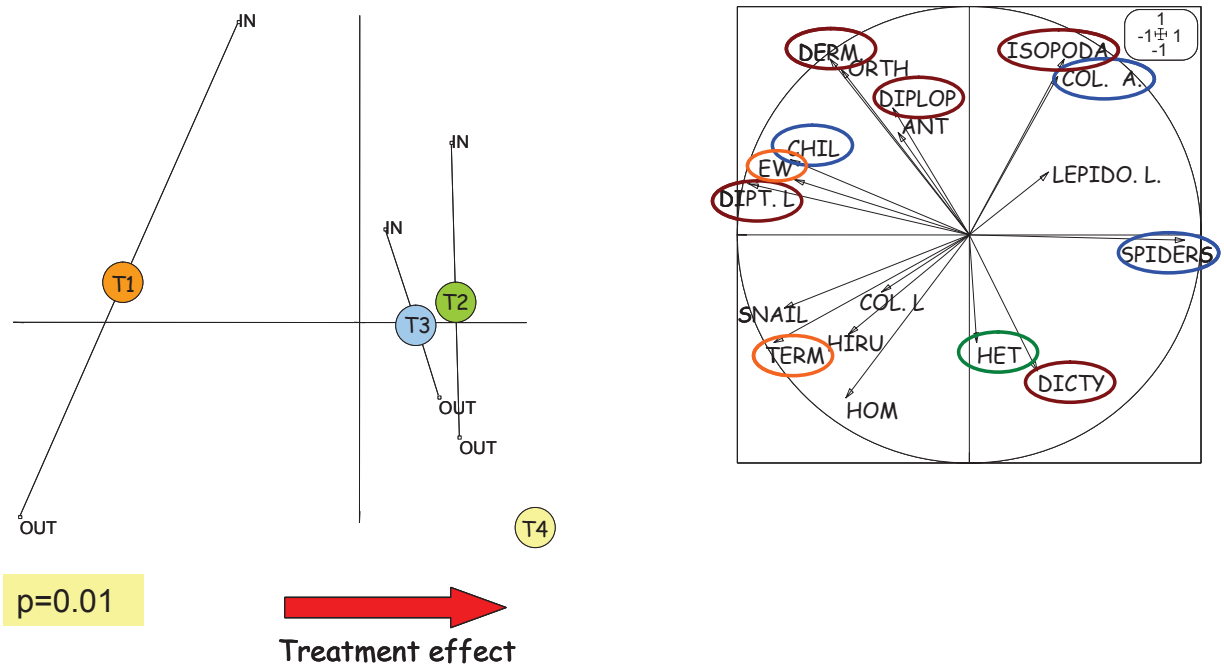


Figure I.29: PCA analysis of macrofauna data collected in October 2005. T1: FBO 100%; T2 and T3: FBO with 50% mineral fertilization; T4: Conventional management. IN: inside FBO trenches; OUT: outside trenches.

Soil aggregation what also greatly enhanced by the FBO application especially below 10 cm depth (Figure I.30).

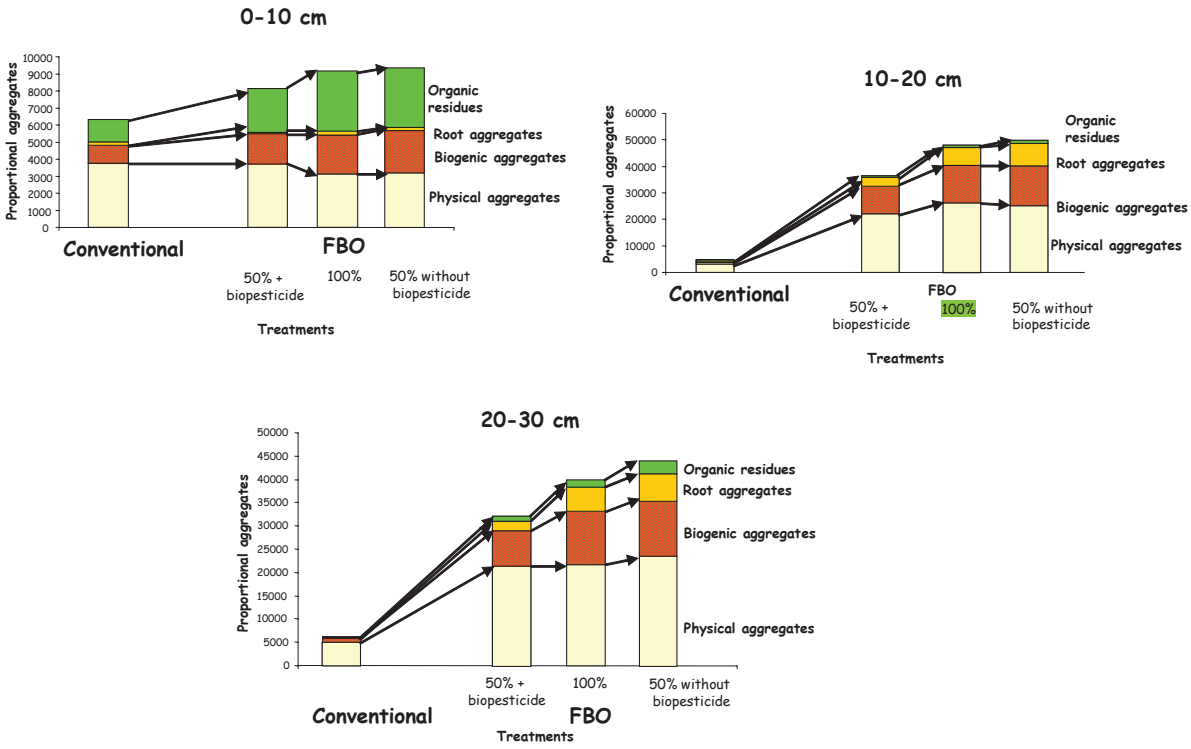


Figure I.30: Aggregation of soil in conventional treatment and FBO trenches (data Elena Velasquez)

All aggregate classes were enhanced, and aggregation started to improve also outside the trenches (data not shown).

Sub indicators and the GISQ showed rather significant variations (Table I.27). Indicator values varied rather significantly in the control itself showing some temporal variability linked either to farming practices (effects of application of fertiliser on chemical and physical properties) or to climatic variations (macrofauna).

The most consistent changes occurred at 12 months when changes in soil macrofauna induced clear improvements in morphology. Sub Indicator values for these two characteristics went beyond the maximum observed in the general study made to calibrate the indicators. Effects were more pronounced in the trenches were earthworms and organic matter had been introduced, but some effects were also visible outside the trenches. This shows that improvement of soil quality was starting

to spread from the managed islands of high ecological functionality to the whole plot.

Table I.27: values of the five sub indicators and General Indicator of Soil Quality, at the onset of the FBO application, after 6 months, inside and outside the trenches, and after 12 months (data and calculations provides by Elena Velasquez and Nuria Ruiz). Underscored values are higher than values in conventional treatment taken at the same time.

Time (months)		Sites	Chemical	SOM	Physical	Fauna	Morphology	GISQ	GISQ/control
0	Control	Tea1, 7	0.25	0.57	0.22	0.23	0.48	0.31	1.00
0		Tea1, 8	0.1	0.3	0.2	0.14	0.3	0.10	1.00
0		Tea1, 9	0.35	0.29	0.31	0.11	0.48	0.18	1.00
6	Outside	Tea1, 7	1.34	0.23	0.37	1.69	0.27	1.06	1.65
6		Tea1, 8	1.76	0.46	0.23	0.08	0.34	0.50	0.67
6		Tea1, 9	0.58	0.74	0.52	0.08	0.33	0.42	1.10
6	Trench	Tea1, 7	1.51	0.24	0.43	0.09	0.29	0.36	0.54
6		Tea1, 8	1.50	0.36	0.32	0.09	0.23	0.38	0.51
6		Tea1, 9	1.76	0.94	0.54	0.09	0.35	0.79	2.07
6	Control	Tea1, 7	2.02	0.64	0.34	0.08	0.22	0.64	1.00
6		Tea1, 8	2.79	0.50	0.24	0.09	0.30	0.75	1.00
6		Tea1, 9	0.75	0.61	0.49	0.08	0.27	0.38	1.00
12	Outside	Tea1, 7	0.98	0.40	0.33	0.10	0.91	0.45	1.67
12		Tea1, 8	1.17	0.33	0.20	0.67	0.87	0.70	2.19
12		Tea1, 9	0.48	0.47	0.49	0.67	0.79	0.64	2.46
12	Trench	Tea1, 7	1.23	0.40	0.22	0.37	1.75	0.80	2.96
12		Tea1, 8	0.64	0.33	0.12	1.76	1.52	1.23	3.84
12		Tea1, 9	0.54	0.47	0.37	0.38	1.60	0.67	2.58
12	Control	Tea1, 7	1.00	0.10	0.35	0.10	0.73	0.27	1.00
12		Tea1, 8	0.78	0.26	0.23	0.10	0.91	0.32	1.00
12		Tea1, 9	0.55	0.27	0.34	0.11	0.79	0.26	1.00

A PCA analysis of data contained in table I.28 showed that changes observed are globally significant. Axis 1 (40.5% of variance explained) indicated changes in soil macrofauna communities and associated improvement in soil morphology. Soil in trenches 12 months after FBO application was clearly separated along this axis from the others. Axis 2 (25.6%) indicated changes in chemical, organic matter and physical indicators. They were more associated to seasonal variations following application of fertilisers and their placement in small trenches dug at the soil surface.

GISQ values were significantly enhanced as compared to control treatment only 12 months after application of the technique. Although effects were more visible in

trenches with GISQ values 2.5 to 3.8 higher, significant improvement was also recorded outside the trenches (values 1.7 to 2.5 times the controls).

Interestingly, the improvement of soil quality did not have an impact on plant production at that stage, although a 15% increase in tea quality (assessed by taste assessment tests) was recorded.

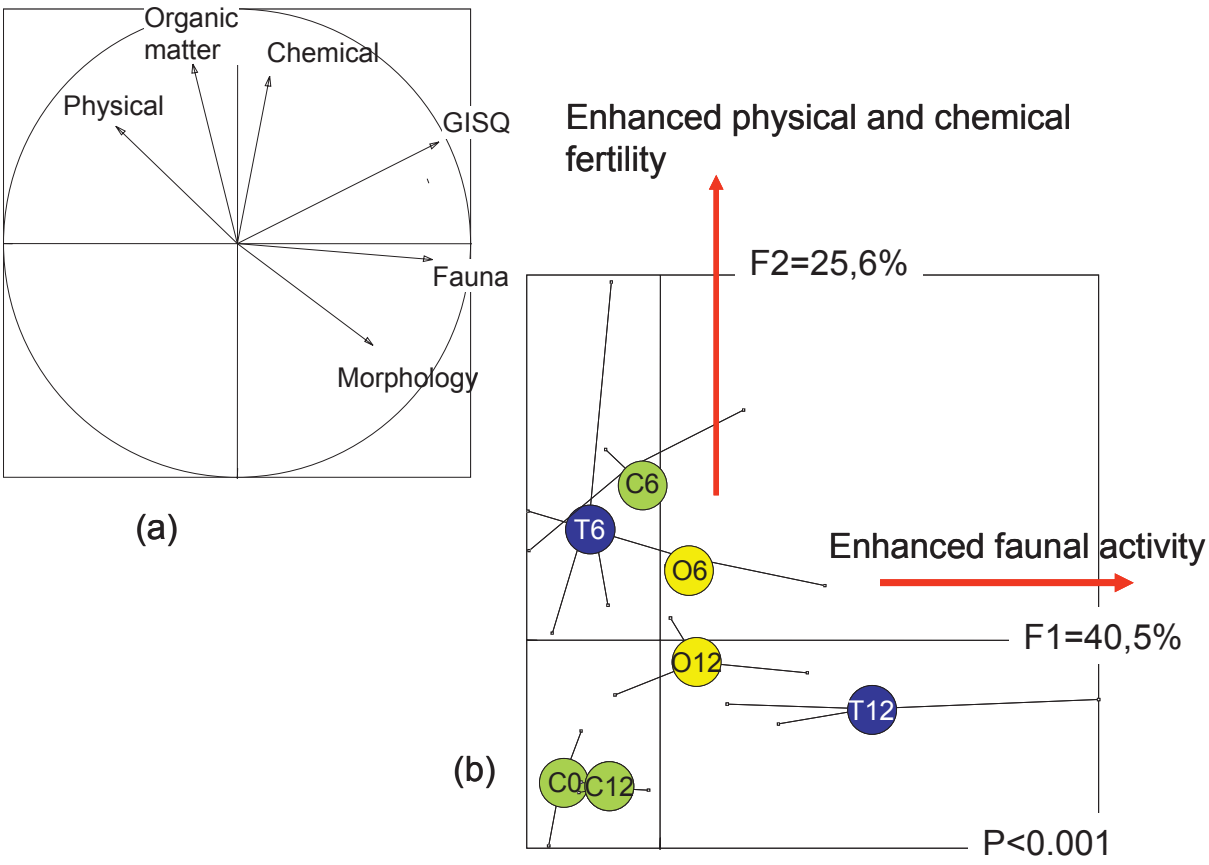


Figure I.31: Projection of treatments in factorial plane defined by the main two factors. C0: values before onset of experiment; C6 and C12: plots maintained with conventional management; T6 and T12: FBO trenches at 6 and 12 months respectively; O6 and O12: outside FBO trenches in plots with FBO management, 6 and 12 months respectively after the onset of the experiment. P: permutation test on PCA coordinates.

I.10 Discussion and conclusion

Soil quality research differs from some soil management research in that it emphasizes the multifaceted nature of soils and requires that physical, chemical, and biological aspects of the soil be considered simultaneously. Multivariate statistics are powerful tools for this integrated assessment and can help soil researchers to extract synthetic information from large sets of data.

Multivariate principle component analysis were carried out in our study on sets of data that characterized respectively soil physical, chemical, organic matter, macro invertebrate and morphology conditions for 20 sites reprersentative of the diversity of agro ecosystems in the study area. Sub-indicators were calculated from each of these data sets based on variables that had the largest importance in determining principal components; a General Indicator of Soil Quality was further established following the methodology designed by Velasquez *et al.* (2007).

The orange plantation had the maximum general indicator of soil quality among the 20 sites, with maximum values of the chemical, physical and macrofauna sub-indicators. This site had been planted to orange trees 5 yarsr ago, manure was applied every winter in trenchs (20cm in depth); N, P, K chemical fertilizer and lime was applied on soil surface. Lime is commonly added to soil to increase pH often resulting in increased microbial activity and contributing to higher SOM and increased aggregation (Haynes and Naidu, 1998). Highest pH was actually found and exchangeable K^{+}, Ca^{2+} and Mg^{2+} were also high. Soil texture was clearly different from other sites, with highest silt percent (58.5%) and very low clay concentration (18.6%). Medium values of organic matter (0.46) and morphology sub-indicators (0.62) were also measured in this orange plantation. Compared with sugarcane plantation and tea plantations in Shanmingxuan tea garden (Tea2), there was little residues cover on the soil of orange plantation.

Shangmingxuan tea gardens (Tea2) had been planted to tea nearly 30 yrs ago. Chicken and cow manures were applied in trenches, together with P fertilizer once a year in Tea2, 12; this plot had the second highest general indicator of soil quality (0.71). Maximum organic matter sub-indicator was found in this site and morphology,

macrofauna and physical sub-indicators had high values.

Site Tea2, 15 received chicken manure once a year; it had a slightly lower general indicator of soil quality (0.68) than Tea2, 12.

Sites Tea2, 13 and Tea2, 14, received Urea and spray fertilizer for leaves. They had lower values for the general indicator of soil quality (0.61 and 0.51 respectively) than the other two tea plantations in the same group. Tea2, 15 and Tea2, 12 were separated from the other two tea plantations in Tea2 by soil morphology as they had more biogenic aggregates while the others had more physical aggregates.

The different results for the four tea plantations in Tea2 might be attributed to different fertilizer applications. Compared with mineral fertilizers or pesticides, the use of manures and organic residues clearly improves soil quality, help to naturally control pests and improve soil C storage. Soil morphology sub-indicators seem to be greatly affected by the type of fertilizers applied.

The major difference between T1 and T2 tea plantations was in fertilizer applications: while T2 received organic fertilizers, T1 were amended with chemical fertilizers. As a consequence, T2 sites had larger microbial biomass carbon and higher values of the soil organic matter sub-indicators (from 0.75 to 1.0) that Tea1 sites (Annexe, table 6).

Bamboo forest had a rather similar value of the general indicator of soil quality (0.54) than sugarcane plantation (0.53). Bamboo forest had a thick residue cover of bamboo leaves and sugarcane plantation had abundant plant residues applied at the soil surface every year. The return of plant residues to soil is known to improve soil structure (Martens, 2000), since mulches buffer temperature and moisture regimes and feed abundant soil fauna that incorporates C to soil. Practices that favour the maintenance or build-up of soil organic matter, such as addition of plant residues, manure or compost, help to conserve soils by improving many properties while reducing the risk of soil erosion (Karlen et al., 1992; Duiker and Lal, 1999; Jacinthe et al., 2002).

Plantations with general indicator of soil quality higher than 0.51 all had higher macrofauna population density (from 454.4 ind m^{-2} - Tea2, 14 to 1036.8 ind m^{-2} - sugarcane) (except for Tea1, 6) with high proportion of Oligochaeta (from 23.2% in

Tea2, 13 to 82.2% in Tea2, 12). High Oligochaeta and Chilopoda density were found in orange plantation which had high contributions to factor 1 and 2 of the PCA performd on macrofauna data (Figure I.23; Figure I.24). Reason for this connection is explained by the influence of soil fauna populations on soil biological processes, nutrient cycling and soil structure, and hence a significant support to the provision of ecosystem services by soils (Lavelle *et al.*, 2006). The interrelationship of the organisms to their abiotic environment and the course of successions of microorganisms during the decomposition of dead plant material are all part of a self-regulatory process which determines to a great extent a site-specific soil fertility (Lavelle, 1997; Beare *et al.*, 1995). These sites also had more large and medium size biogenic aggregates as a consequence of enhanced macro invertebrate activities.

Renewal of trees in search for better tea varieties had occurred in most plantations at the Yingde tea institute (Tea1) during the past 20 years. Tea trees had been planted 2 to 20 years ago in the 11 studied sites, in old tea gardens, reclaimed land or other plantations. This management history seems to have had negative effects on macro invertebrate communities since less macrofauna biodiversity and lower population densities were found in tea plantations in Tea1 than in other plantations (Figure I.23). Species diversity was affected by soil management practices; generally intensive agricultural practices decrease biodiversity while the natural practices have an inverse effect (Lavelle *et al.*, 2006).

Tea plantations in Tea1 were conventionally managed, with intensive applications of chemical fertilizers and pesticides. They had similar manure applications (once every 3-4 years), chemical fertilizers (3 times a year) and pesticides (5-6 times a year).

Tea1, 11 was a site with 15 yr tea plantations and much more residues were returned to soil than in other sites in Tea1, hence, macrofauna density and organic matter sub-indicator had significantly higher values than in other T1 sites. On the contrary, Tea1, 2 that had been reclaimed from wasteland three years ago had the lowest macro invertebrate communities (Hemiptera, Formicidae and Lepidoptera, larva). This may have been partly the result of tillage that disrupted the soil habitat

with severe consequences expected on the density of invertebrates through immediate killing or impairment of the natural habitat. Tillage also strongly influences SOC distribution and storage by physically mixing soil and by distributing crop residues in the soil (Wander and Bollero, 1999; Liebig *et al.*, 2004).

Tea plantation Tea1, 8 in tea institute had the lowest general indicator of soil quality; soil was clayed (clay = 59.3%) and acidic (pH = 4.26), with poor total C (11.1‰) and nitrogen (0.9‰) content. Medium macrofauna density (451.2 ind m^{-2}) was found with high Formicidae (390.4 ind m^{-2}) and very low Oligochaeta density (6.4 ind m^{-2}) in it. The site had more physical aggregates (127 unites) than biogenic aggregates (46 unites).

General indicator of soil quality was low for wasteland (0.20) that was regularly flooded (3 times in 10 years) because of its low location, with no plant cover except for some sparse ruderals. High content in fine sands and less macrofauna activities (similar with Tea1, 8) resulted in a high bulk density (1.49 g cm^{-3}), and many stones (188 units) were separated by morphology analysis providing evidence for severe erosion.

Pine forest had a low general indicator of soil quality (0.30). It was an artificial secondary forest, planted less than 10 years ago. Soil clay content was relatively low (34.9%) and pH was slightly acidic (pH = 5.25), with very low exchangeable K^{+}, Ca^{2+} and Mg^{2+} (4.3, 513, 28.1 mg kg^{-1} respectively). Not much macrofauna (400 ind m^{-2}) was found, but the large number of medium size biogenic aggregates (256 units) may have been produced by numerous Oligochaeta (76.8 ind m^{-2}).

General indicator of soil quality separated plantations and sites significantly according to their locations, plantation histories, fertility and tillage management. Generally, manures and residues could improve soil organic matter, macrofauna activities and biogenic aggregates. High frequency of chemical fertilizer utilisation acidified soils and had negative effects on soil macro invertebrate biodiversity and population density.

The FBO technology applied to three tea plantations in tea institute (Tea1) significantly improved soil quality. GISQ had increased from 2.6 to 3.8 times as

compared with conventional control inside the trenches, 12 months after FBO application. Improvement was also observed outside the trenches with 1.7 to 2.5 fold increases. Improvement was mainly due to increases in macrofauna and morphology sub indicators.

The GISQ methodology allowed to ordinate soils with different management practices and cropping histories; the use of five sub indicators allowed to assess their respective strengths and deficiencies in terms of soil quality. Changes in soil quality following the application of the FBO restoration technique were accurately monitored and allowed to describe the first steps of restoration after one year.

We recommend to use this methodology to detect any problem or deficiency in managed soils, to compare the value of different management options in providing a wide range of soil ecosystem services, and to monitor changes in soils suvmitted to restoration practices.

II

Assessment of soil structure in different types of land-use

Stable aggregates and soil morphology

Résume

La structure du sol est un attribut clé pour son fonctionnement, déterminé par la taille et l'arrangement des particules et des pores. La structure du sol est aussi définie par la taille et la forme des agrégats qui sont formés par l'action des organismes ingénieurs du sol et divers processus physiques, avant d'être stabilisés par la matière organique ou des précipités minéraux. De nombreuses études montrent que la stabilité des agrégats est un bon indicateur de la structure du sol. Dans notre étude, la distribution des agrégats stables est analysée par la méthode de tamisage à l'eau. Les agrégats sont séparés en 5 catégories en fonction de leur diamètre: >2000, 1000-2000, 500-1000, 250-500, 53-250 μm. La moyenne géomètrique du diamètre (MGD) est utilisée pour indiquer la distribution des agrégats stables. Une méthode d'analyse morphologique du sol consiste à séparer d'une manière visuelle des agrégats et autres objets du sol comprenant des racines, des tiges, des graines, des graviers, des petits boutd de bois et les invertébrés. En fonction de leur forme, taille et couleur, on réconnait les agrégats biogéniques produits par les macro-invertébrés, et les agrégats physiques produits par les processus physiques. Parmis les 20 parcels sur les quelles l'indicateur de qualité du sol est étudié, nous avons choisi 6 plantations du thé pour une étude comparative de la structure du sol par les techniques de tamisage à l'eau et l'analyse de la morphologie du sol. L'analyse de la morphologie du sol a pour but de décrire l'origine des agrégats et l'analyse par la technique de tamisage à l'eau donne l'information sur la stabilité des agrégats, quelle que soit leur origine.

L'analyse de la distribution des agrégats stables montre qu'il existe une correlation positive entre la MGD et la teneur en argile du sol dans la couche du sol de 0-10 cm. et la teneur totale du sol en carbone dans les deux couches superficielles (0-10 cm et 10-20cm). L'apport du mulch et des résidus organiques a ainsi pour effet de protèger les macro-agrégats.

L'analyse morphologique du sol montre que l'apport de matière organique augmente la quantité d'agrégats biogéniques. Les deux méthodes ont révélé des différences entre les plantations, mais il n'y a pas de corrélation entre les objets de morpholoie distincts et la MGD.

Mots clés: Structure du sol; la stabilité des agrégats; morphologie du sol; administration du sol

Abstract

Soil structure is a key factor in the functioning of soil, it refers to the size, shape and arrangement of solids and voids, continuity of pores and voids. Soil structure is sometimes defined from the size and shape of soil aggregates held together by organic matter and other chemical precipitates. Many studies show that aggregate stability is a good measurement of soil structure. Aggregate stability distribution was studied by wet-sieving method in our study, aggregates were separated into five classes: 2000, 1000, 500, 250 and 53μm, geometric mean diameter (GMD) was used to indicate soil aggregate stability distribution. We used a method of soil morphology as an assessment technique of soil structure based on a visual method of the separation of different aggregates and other items that comprise the soil derived from Topoliantz *et al.* (2000). Aggregates were classified as "biogenic" clearly produced by macroinvertebrates and physical aggregates produced by physical processes, they were classified according to their shape, size and colour. Roots, stems, seeds, stones, woods and invertebrates were separated at the same time. Six tea plantations with different GISQ (different soil management histories, tillage and fertilization practices) among the twenty plots studied for soil quality indicator were chosen to a comparative study of soil structure attributes by wet-sieving and soil morphology analysis. Soil morphological analysis had a different aim compared with aggregate stability that it first seeks to describe the origin of the aggregates, on the other hand aggregates stability by wet-sieving gives information on aggregates resist slaking.

Results of aggregate stability distribution showed that positive correlations were found between clay percent and GMD for soils from 0-10 cm but not for soils from 10-20 cm, while total soil C and GMD had positive correlations for both layers. Highest GMD was found in site planted tea trees for 20 years with chemical fertilizers applied (Tea1, 1; soil samples taken from 0-10 cm), and site planted tea trees for 15 years with manure and chemical fertilizers and lot residues applied (Tea1, 11; soil samples taken from 10-20 cm). Residues and mulches could protect big macro-aggregates.

Soil morphology study showed that site planted tea trees for 30 years with manure of chicken and cow applied (Tea2, 12) has the most quantity of aggregates, while it has the highest proportion of biogenic aggregates. Increasing organic matter inputs by manure and residues resulted in more biogenic aggregates. Both methods showed significant difference between the six plots. Aggregates stability distribution measured by GMD is found to be independent on biogenic or physical classification measured by morphological analysis.

Keywords: Soil structure; Aggregate stability; Soil morphology; soil management

Ⅱ.1 General introduction

Ⅱ1.1 Basic concepts of soil structure, a key factor in soil function

Soil is a dynamic and highly structured substrate, home to a myriad of organisms, each with a potentially important role in the present and future viability of soils to produce sufficient food, absorb pollutants, maintain hydrological cycles and other ecosystem services (Erhlich and Erhlich, 1992). Soil physical properties are usually recognized as important soil quality indicators (Karlen and Stott, 1994; Arshad *et al*., 1996; Boix-Fayos *et al*., 2001). In China, severe soil erosion has resulted in both large losses of soil and nutrients, and severe degradation of soil physical properties, such as increased bulk density, reduced aggregate stability and reduced water retention (Zha and Tang, 2003). This is usually described as "deterioration of soil structure", a term that includes a broad range of soil processes and soil physical conditions (Alegre and Cassel, 1996) and is often related to land use and soil/crop management practices. Generally, soil structure largely determines soil physical properties and their functions (Dexter, 1997). Soil structure is a key factor in the functioning of soil, its ability to support plant and animal life, and moderate environmental quality with particular emphasis on soil carbon (C) sequestration and water quality.

Soil structure has been variously defined but in the broadest sense can be described as the spatial arrangement or heterogeneity of soil particles, aggregates, and voids or pores (Carter and Stewart, 1996; Kay and Angers, 1999). Soil structure refers to the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development (Lal, 1991). Soil structure is sometimes defined from the size and shape of soil aggregates held together by organic matter and other chemical precipitates. Soil structure is an important soil property to be evaluated because it mediates many biological and physical processes in soils. For example, soil structure determines porosity and infiltration, hence water availability to plants, movements of roots and invertebrates and susceptibility to soil erosion. Since soil structure also influences losses of agrochemicals, sequestration of

C, and N gas losses, it is an important attribute to enhance to reduce the negative environmental impact of agricultural practices.

Soil structure affects plant growth by influencing root distribution and the ability to take up water and nutrients (Rampazzo *et al*., 1998; Pardo *et al*., 2000). Soil structure facilitates oxygen and water infiltration and can improve water storage (Franzluebbers, 2002). Increased water transfer through soil can reduce fertilizer retention in the soil matrix and fertilizer use efficiency in plants (Franzluebbers, 2002). Disturbance of soil structure through compaction or tillage can result in the rapid recycling of nutrients, crusting, reduced water and air availability to roots.

Aggregate stability is often used as a measurement of soil structure (Six *et al*., 2000b).

Ⅱ1.2 Soil structure formation and factors affecting these processes

The on-going interactive effects of soil-forming processes, soil properties and exogenous factors such as geomorphology and climate establish a dynamic equilibrium in soil structure (Figure Ⅱ.1). Soil structural development and aggregation occur within the context of natural pedogenic processes and anthropogenic activities. Soil properties, such as the nature of bedrock, texture, pH, cation exchange capacity (CEC) and porosity also affect the formation of soil and its structure.

In the hierarchy of factors that determine soil function, biological processes are proximal determinants that have profound effects on the creation and maintenance of soil structural features (Lavelle *et al*., 1993).

Over 40000 bacterial species exist within 100g of soil (Torsvik *et al*, 1990), and all of the 11 terrestrial animal phyla have representatives that spend at least part of their lives in soil. These diverse organisms range in size from unicellular bacteria to vertebrates and have a parallel sequence of spatial influence on soil structure.

The activities of soil organisms influence C retention time and turnover in soil which in turn affect C stabilization, aggregation of soil particles and the turnover of aggregates. Decomposition is effected by the activity of soil organisms, that are in turn influenced by soil properties, climatic factors (temperature, moisture) and

gaseous concentration (Christensen, 2001).

Soil animals, especially the ones called ecosystem engineers are strongly associated with soil structure formation and are major determinants of soil processes influencing nutrient cycling, aggregate formation, and permeability of soil (Lavelle *et al*., 1997; Lavelle *et al*., 2006). Foraging, respiration and defecation by soil mesofauna can transport and transform soil organic carbon within pore spaces and so influence the stability and cohesion of microaggregates (Foster, 1988). The burrowing activity of earthworms and termites that have effects on porosity, bulk density and infiltration are familiar (Lavelle *et al*, 1994). Activity of soil fauna is important in the formation of organo-mineral complexes and aggregation and the formation of large soil pores that play an important role in preferential flow.

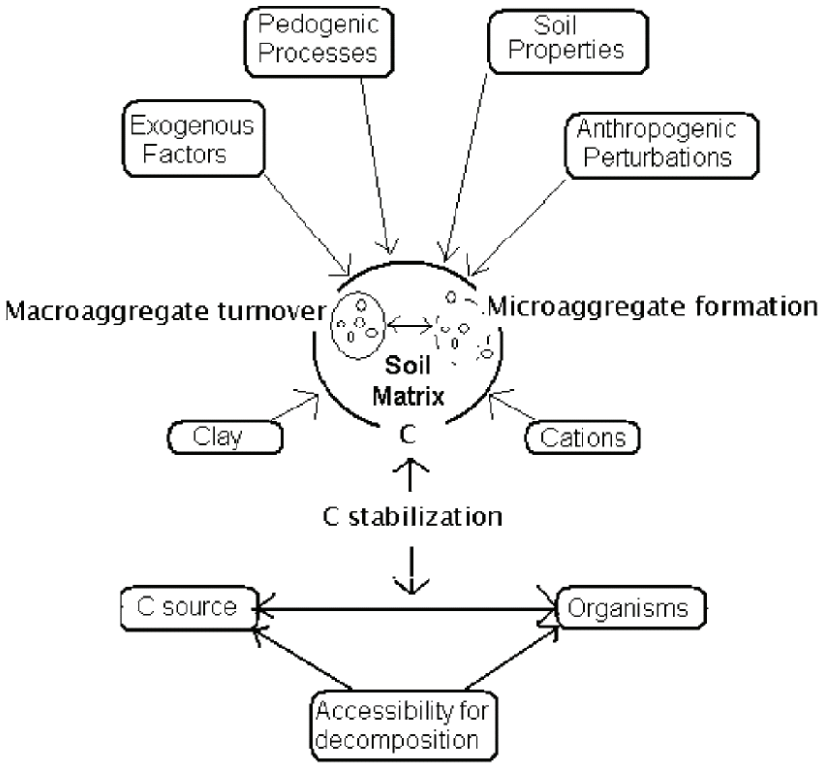


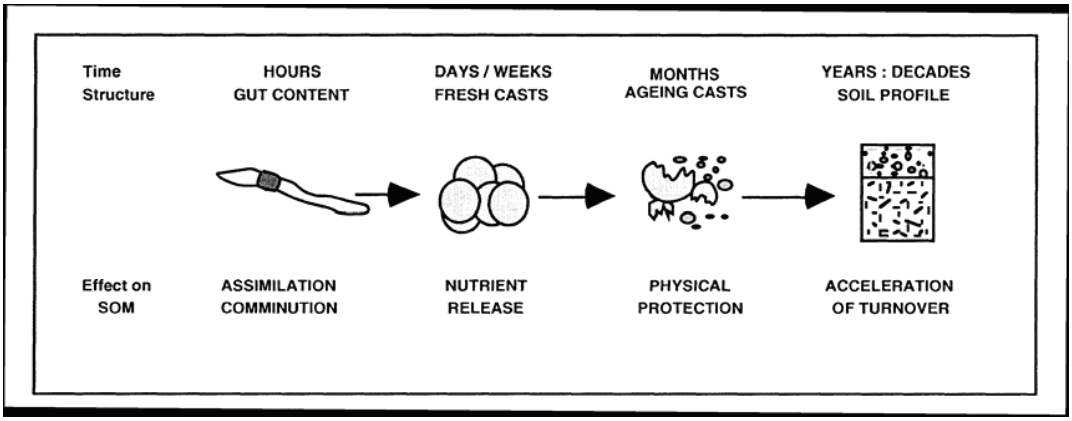
Figure II.1: Factors affecting soil aggregation (Bronick and Lal, 2005).

All the invertebrate soil ecosystem engineers influence soil physical structure. They ingest and egest soil material, relocate plant material and form burrows (Amezketa, 1999). Organic matter contained in biogenic structures formed by soil organisms such as termite mounds and earthworm casts is often protected from mineralization (Lavelle *et al*, 2004a). The effects of these activities may however greatly vary depending on the scales considered (Figure Ⅱ.2). Generally, SOM dynamics are accelerated at small scales of time and space (e.g., during gut transit, or in freshly deposited biogenic structures) and slowered at larger scales (e.g., that of ageing biogenic structures, as long as they maintain their cohesion).

Biological activity can also, under specific circumstances, degrade soil properties by removing dissolved organic matter (DOC) and breaking down bonds between particles during ingestion. The dispersion is often compensated for during reformation of aggregates and egestion of recalcitrant C (Cr) compounds that lead to the formation of new stable aggregates. Ingested soil undergoes many alterations including physical realignment of clay particles and breaking of bonds within soil aggregates to alter microbial accessibility to soil organic carbon (SOC) (Wolters, 2000). Feeding, mixing ejecta with soil, reworking and biosynthesis of SOC generally result in an increase in soil C_R (Wolters, 2000).

Activity of soil fauna is important in the formation of organo-mineral complexes and aggregation. Ingested soil undergoes many alterations including physical realignment of clay particles and breaking of bonds within soil aggregates to alter microbial accessibility of SOC. Feeding, mixing ejecta with soil, reworking and biosynthesis of SOC generally result in an increase in soil C_R (Wolters, 2000).

The impact of earthworms burrowing and casting and casting activities in the creation and dynamics of soil aggregation has been widely investigated (Blanchart *et al*., 1997; Lavelle *et al*., 1997; Decaens *et al*., 1998; Topoliantz *et al*., 2000) (Figure Ⅱ.2).



Source: Lavelle, 1997

Figure II.2: Regulations of decomposition in the drilosphere

As increasing numbers of researchers focused on the activity of earthworms, special interest has been set on the earthworms' key role in the formation and stabilisation of soil aggregates and nutrient cycling (Lee and Foster, 1991; Lavelle et. al, 1997) as they remove plant litter and other organic materials from the soil surface and incorporate them into their casts that comprise a large proportion of soil macro aggregates in the upper cm of many soils (Martin, 1991; Blanchart *et al*., 1999). Earthworms ingest organic matter, mix it with inorganic soil material, pass the mixture through their gut and excrete it as a cast. Bioturbation by earthworms not only changes soil drainage properties but also modifies the organization of void space.

Numerous studies showed a higher stability in earthworm casts than in the surrounding soil aggregates (McKenzie and Dexter, 1988; Shipitalo and Protz, 1988; Marinissen, 1994). However, the casting activities only enhance aggregate stability if the casts are dried or aged (Shipitalo and Protz, 1988; Marinissen and Dexter, 1990). In addition, the stability of the casts depends on the quality of the ingested organic matter and soil texture (Shipitalo and Protz, 1988) and the amount of castings also depends on the feeding activity.

Soil-feeding termites form microaggregates either by passing soil material through their intestinal system and depositing it as fecal pellets or by mixing the soil with saliva using their mandibles (Bignell and Holt, 2002).

Ⅱ1.3 Main methods for the study of soil structure

Soil structure has been traditionally considered as one of the main attributes of soil quality and the qualitative role of soil structure in soil hydrology is well documented in the literature at the pedon scale. From the level of clay particles and clay–organic matter complexes to the spatial arrangement of peds and clods in the soil profile, the scale of soil structure can range over several orders of magnitude. At each level, soil structure directly and indirectly impacts on soil–air–water relations and processes, while such processes are modified by soil and plant management.

Macro- and micro-morphology are attributes of soil structure that affects hydraulic functions and other soil physical properties

Field morphological methods describe soil profiles, from the different holorganic layers (Ol, Of and Oh) to the different subsequent A, B and C horizons, and the specific natural (concretions, lixiviations, translocations) and anthropogenic (erosion, ploughing pan) macrofeatures.

Soil micromorphology is based on the analysis of thin sections prepared from undisturbed blocks of soil. Thus, it provides a method for studying the interactions between fauna and soils, as demonstrated in the study by Bal (1970) who investigated the extent to which soil fauna influenced the development of humus profiles under two contrasting fruit tree types. The Velasquez *et al* (2006) method is an intermediate method based on visual assessment of aggregates and other features, that allows to get a much larger amount of data than observation of undisturbed thin sections for the large amount of work required by the last method.

Another widely used approach is the direct separation and measurement of the amount of stable aggregates that is aggregates that have resisted aggressive methods of soil mechanical of chemical disruption. Many studies claim that aggregate stability is a good measurement of soil structure and erodibility (Chan and Mead, 1988; Six *et al*., 2000b), as it describes the ability of the soil to retain its arrangement of solid and void space when exposed to different stresses (Kay, 1990).

Aggregate stability affects soil strength and, therefore, the soil's ability to transmit liquids and gases, which are important functions for crop production and

ecosystem health. Because aggregate stability is an indicator of vital soil functions, it can be used to assess soil quality and its response to soil management options (Topp *et al*., 1996; Boehm and Anderson, 1997).

In this work we assessed soil structure using a simple visual method to separate aggregates and other items that comprise the soil derived from Topoliantz *et al*. (2000)(Velasquez, 2004; Velasquez *et al*, 2006). This method assesses soil morphology at an intermediate scale between field macro- and micro-morphology on thin soil sections and allows treating large numbers of samples.

We compared the results of this method with laboratory techniques generally used to assess the amount and mean size of stable aggregates. The aim was to know if the visual method of morphology can be used as a reliable surrogate to the difficult and time consuming physical methods used in the laboratory, or whether these methods are actually complementary, the visual methods providing information on the origins and importance of aggregation, the other one informing on the stability of aggregates and their effects on physical soil parameters.

Ⅱ. 2 Site characterisation

Ⅱ. 2.1 General characterisation

The study sites used for this part of the research were located at the Tea Research Institute, Guangdong Academy of Agricultural Sciences (Tea1) and Shangmingxuan Tea Garden (Tea2, 20 km from site 1), Yingde, Guangdong Province, south of China. They are part of the 20 sites analysed in the first chapter of this work.

Six tea plantations were chosen for this comparative study of soil structure attributes. We looked for sites presenting a wide range of values of the soil quality indicator, soil management histories, tillage and fertilization practices (TableⅡ.1). Two sites from the Tea Institute plantations had relatively poor quality soils (Tea1, 1 and Tea 1,5 with GISQ values equal to 0.30); three sites had intermediate values of 0.51 to 0.55 (Tea 1, 6, Tea1, 11 and Tea2, 14) and a last site, Tea2, 12, had a relatively high (0.71) GISQ value.

Table Ⅱ.1: Sampling sites description and values of the General Indicator of Soil Quality (GISQ) in the 2004 sampling.

Site	Location	GISQ	Description
Tea1, 1	24°18′24 N, 113°23′19 E	0.30	20 years, chemical fertilizer
Tea1, 5	24°18′21 N, 113°23′01 E	0.30	Replanted 2 years ago, chemical fertilizer and manure*
Tea1, 6	24°18′24 N, 113°23′19 E	0.51	20 years, chemical fertilizer and manure*
Tea1, 11	24°18′22 N, 113°23′01 E	0.55	15 years, chemical fertilizer and manure*
Tea2, 12	24°22′13 N, 113°27′55 E	0.71	Ca.30 years, manure of chicken and cow**
Tea2, 14	24°22′13 N, 113°27′55 E	0.51	Ca.30 years, urea and spray fertilizer for leaves***

* Applications of manure 3-4 years once, chemical fertilizers 3 times a year and pesticides5-6 times a year

** Chicken and cow manure and P fertilizer applied once a year

***Urea and spray fertilizer for leaves were applied 3 times a year

Sampling was done in June 2005. In each site, 5 points were chosen the 4 corners and at the centre of the parcels; samples about 500g each were taken at 0-10 cm and 10-20 cm depth for soil basic physical, chemical and organic matter analyses. Undisturbed soil cores, 10×10×10 cm, were taken at the same 5 points for soil morphology analysis. Methods for analysis of soil physical, chemical and organic matter properties were the same as in Chapter I.

Ⅱ. 2.2 Basic biological, physical and chemical properties

Basic biological, physical and chemical properties were studied in the 6 sites (Annexe Table 11; Figure Ⅱ.3-9).

Ⅱ. 2.2.1 Soil microbial biomass carbon

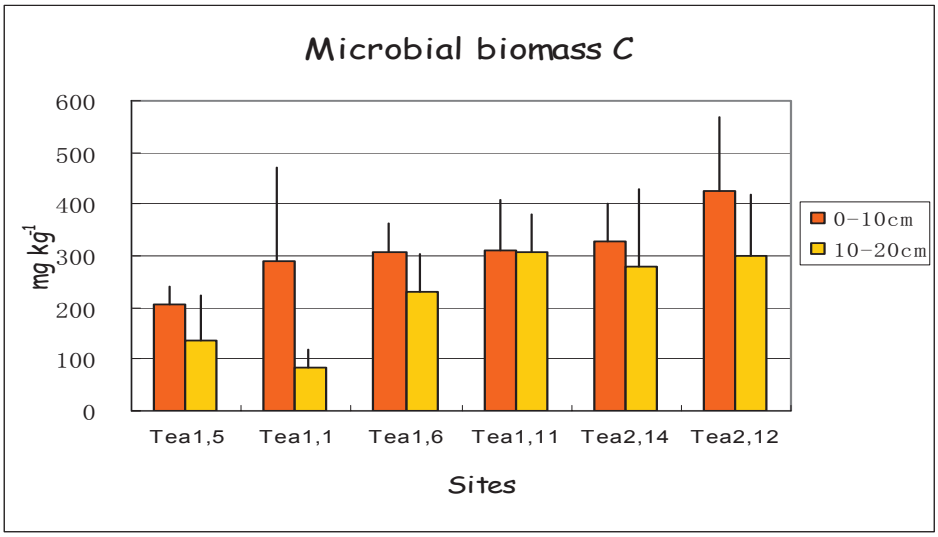


Figure Ⅱ.3: Variations of soil microbial biomass C among the six sites sampled.

As expected, soil samples taken from 0-10 cm had higher Microbial Biomass Carbon (MBC) than samples from 10-20 cm. Large variations were observed between site Tea2, 12 with the highest MBC (425 mg kg^{-1}) and site Tea1, 5, the lowest (136 mg kg^{-1}). Compared with tea gardens in Tea 1, the two sites in Tea 2 had higher MBC, probably a result of different fertilizer practices, with higher amounts of organic matter applied. Difference of MBC among sites for samples from 0-10 cm was not significant (F=2.06; p=0.1066); difference of MBC among sites for samples from 10-20 cm was significant (F=4.02; p=0.0086).

Ⅱ. 2.2.2 Soil respiration for 7 days

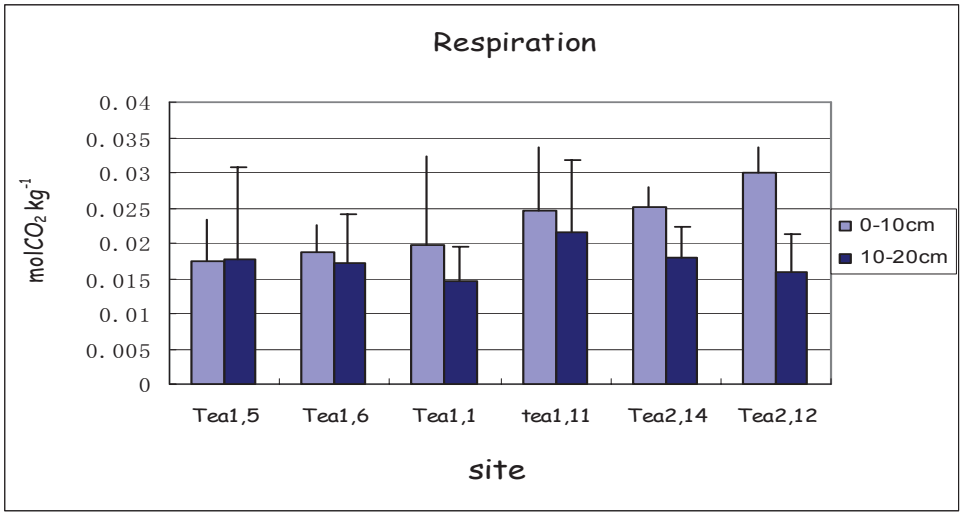


Figure Ⅱ.4: Variations of soil respiration for 7 days in standard laboratory conditions among the six sites sampled.

Soil respiration values followed soil microbial biomass carbon. Site Tea2, 12 had the highest respiration rates (0.0301 mol CO_2 kg^{-1}) and site Tea1, 5 had the lowest value (0.0175 mol CO_2 kg^{-1}). Difference of soil respiration among sites for samples from 0-10 cm and 10-20 cm were not significant (F=2.25, p=0.0818 and F=0.45, p=0.45 respectively).

Ⅱ. 2.2.3 Ration of soil respiration and microbial biomass carbon

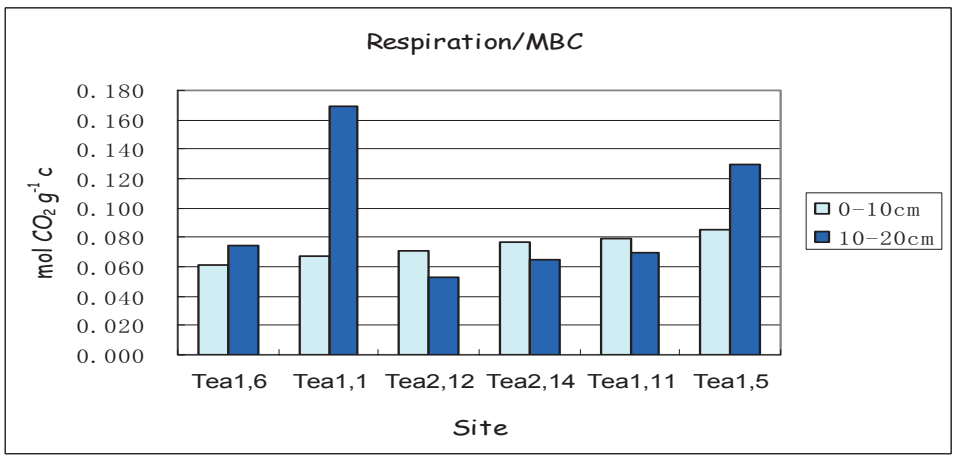


Figure Ⅱ.5: Variations of ratio of Soil respiration and Soil microbial biomass C among the six sites sampled.

Most soil samples had soil respiration and microbial biomass C ratios between 0.06 to 0.08, except for 10-20 cm strata of sites Tea1, 1 and Tea1, 5 that are much higher (0.170 and 0.130 respectively).

Ⅱ. 2.2.4 Total carbon

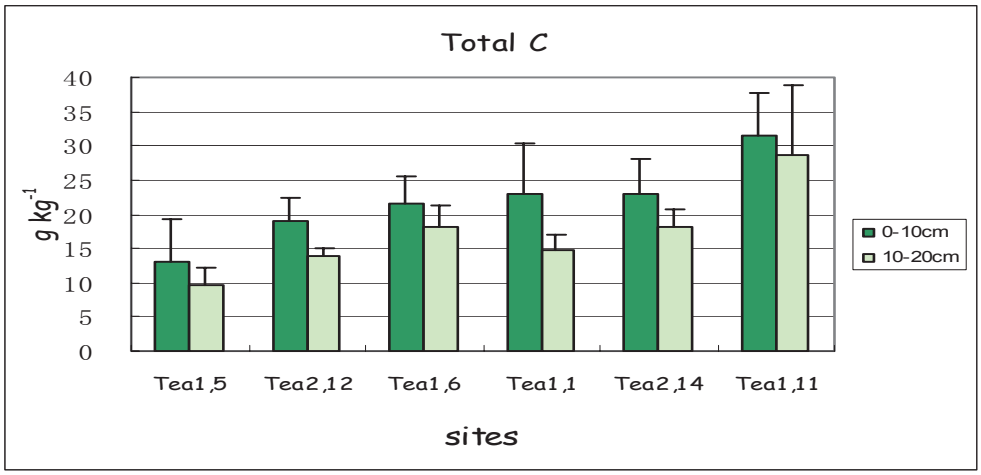


Figure Ⅱ.6: Variations of total soil carbon content among the six sites sampled.

Site Tea1, 11 had the highest total carbon (22.98 g kg^{-1}; 0-10 cm) and Tea1, 5 had the minimum (9.77 g kg^{-1}; 10-20 cm). There was no great difference between the other four sites in two groups. Difference of total carbon content among sites for samples from 0-10 cm and 10-20 cm were both significant ($F=5.88$, $p=0.0011$ and $F=9.62$, $p=0.0001$ respectively).

Ⅱ. 2.2.5 Soil bulk density

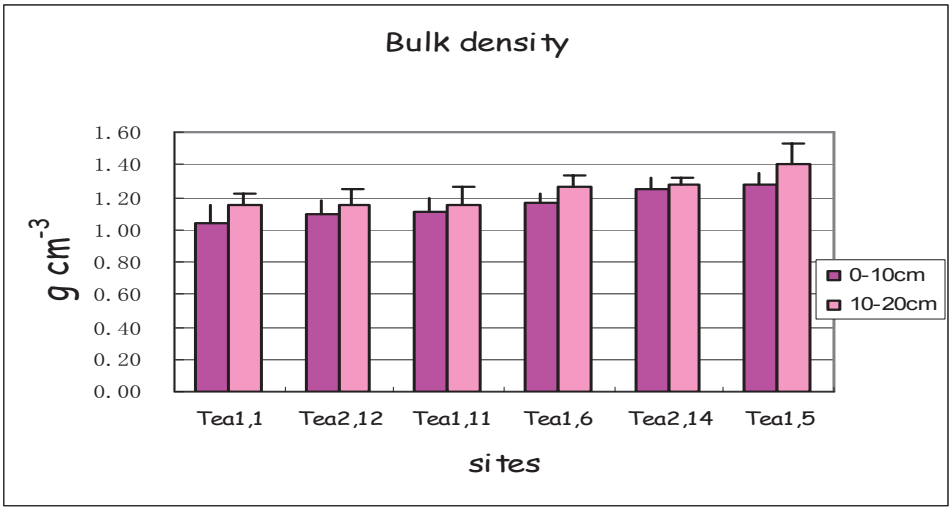


Figure Ⅱ.7: Variations of soil bulk density among the six sites sampled.

Site Tea1, 5 that had been recently replanted (2 years ago), had a fine sandy texture and the highest bulk density (1.27 g cm^{-3}) as compared with the other sites. Difference of bulk density among sites for samples from 0-10 cm and 10-20 cm were both significant (F=7.00, p=0.0004 and F=6.93, p=0.0004 respectively).

Ⅱ. 2.2.6 Soil texture

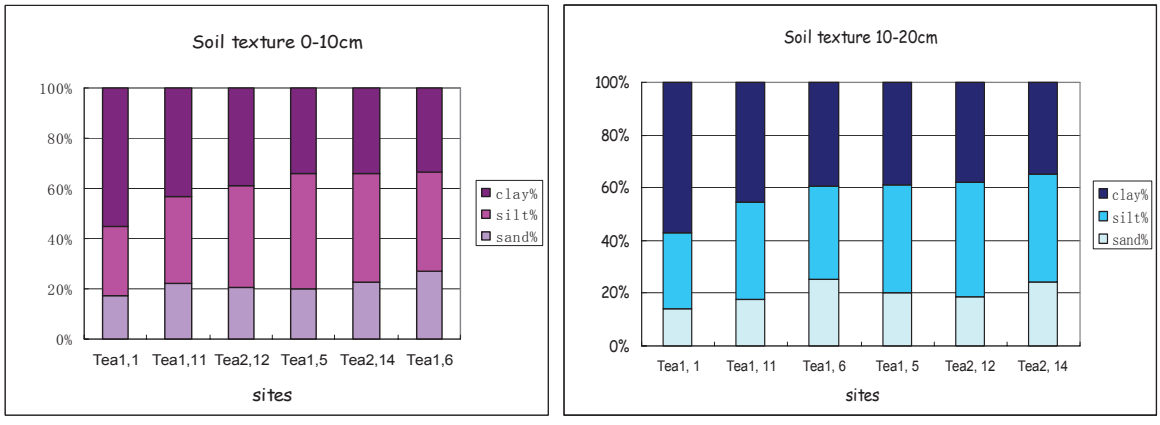


Figure Ⅱ.8: Variations of soil texture among the six sites sampled.

Site Tea1, 1 had the highest clay content (55.1% and 57.3% respectively for samples from 0-10 cm and 10-20 cm); Tea1, 6 had the highest sand content (26.9% and 25.2% respectively for samples from 0-10 cm and 10-20 cm). Difference of clay contents among sites for samples from 0-10 cm and 10-20 cm were significant (F=27.24, p=0.0001 and F=23.99, p=0.0001 respectively); Difference of silt and sand percent among sites for samples from 0-10 cm and 10-20 cm were also significant (F=27.24, p=0.0001 and F=23.99, p=0.0001; F=5.32, p=0.0020 and F=8.35, p=0.0001 respectively).

Ⅱ. 2.2.7 Soil pH

Figure Ⅱ.9: Variations of soil pH among the six sites sampled.

All soils were acidic with pH values lower than 5. The lowest values were ca. 4.0 in Tea1, 6. Difference of pH among sites for samples from 0-10 cm and 10-20 cm were both significant (F=7.78, p=0.0002 and F=8.65, p=0.0001 respectively).

Ⅱ.2.3 Multivariate analyses (PCA) for basic biological, physical and chemical properties

A multivariate PCA analysis of sites on a matrix grouping the 8 measured basic parameters separated them significantly (Figure Ⅱ.10; $p<0.001$). Axis 1 of the PCA

(34.4% variance explained) opposed sites 1 and 11 in the Tea Institute plantations, with more clay and organic matter in soils to other sites that had higher pH, were sandy and more compact; axis 2 (28.2% variance explained) opposed sites with high organic status (high total soil C, Microbial Biomass C and respirometric activity) to others. Site 1 in the Tea Institute had the lowest coordinates, and hence lower organic status, than sites outside the Institute plantations.

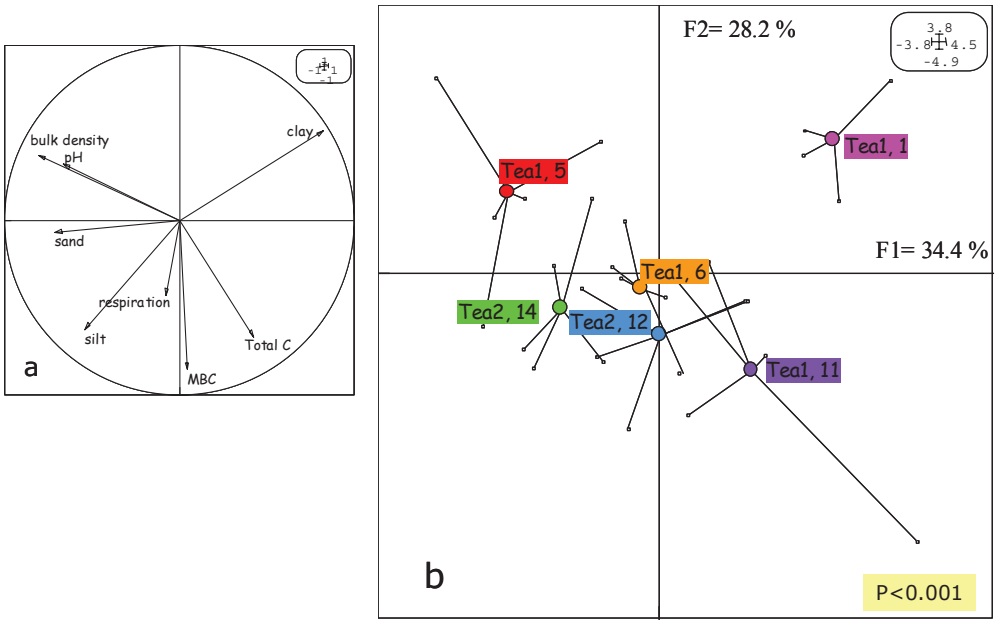


Figure II.10: Projection of sites in factorial space defined by PCA analysis of basic physical, chemical and soil organic matter properties, including soil texture, bulk density, soil pH, soil respiration (7 days), total C and microbial biomass C.
(a) Correlation circle of soil variables with factors 1 and 2 of PCA analysis
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).

Ⅱ.3 Aggregates stability analysed by method of wet-sieving

Ⅱ.3.1 Basic concept of aggregation

Aggregates are stable assemblages of particles formed through the combination of mineral particles with organic and inorganic substances. The complex dynamics of aggregation are the result of the interaction of many abiotic and biotic factors, including climatic factors (e.g. alternating shrink–swell; freeze–thaw; wet–dry states), soil management, soil invertebrate engineers and plant root activities and soil properties such as mineral composition and texture (soil oxide and soil clay content), SOC concentration, pedogenic processes, microbial activities, exchangeable ions, nutrient reserves, and moisture availability (Kay, 1998).

The aggregate hierarchy concept proposed by Tisdall and Oades (1982) is probably the most significant theoretical advancement in the understanding of aggregate–SOM interactions. In the aggregate hierarchy concept it is postulated that the different binding agents (i.e. transient versus temporary versus persistent binding agents) act at different hierarchical stages of aggregation. Free primary particles and silt-sized aggregates (<20 μm) are bound together into microaggregates (20–250 μm) by persistent binding agents (i.e. humified organic matter and polyvalent metal cation complexes), oxides and highly disordered aluminosilicates. These stable microaggregates, in turn, are bound together into macroaggregates (>250μm) by temporary (i.e. fungal hyphae and roots) and transient (i.e., microbial- and plant-derived polysaccharides) binding agents. However, the polysaccharides are believed to mostly exert their binding capacity on a scale <50μm within the macroaggregates. Because of this hierarchical order of aggregates and their binding agents, microaggregate stability is higher and less dependent on agricultural management than macroaggregate stability.

Two years after the publication of the aggregate hierarchy theory, Oades (1984) formulated a small, but later to be found very important, modification to the concept of the hierarchical build up of aggregates (Figure Ⅱ.11). In the hierarchical aggregate model of Tisdall and Oades (1982), it was implicitly understood that aggregates are sequentially formed, i.e. microaggregates are first formed free and then serve as the

building blocks for the formation of macroaggregates. Oades (1984), on the other hand, postulated that the roots and hyphae holding together the macroaggregate form the nucleus for microaggregate formation in the center of the macroaggregate. Since roots and hyphae are temporary binding agents, they do not persist and decompose into fragments. These fragments coated with mucilages produced during decomposition become en-crusted with clays resulting in the inception of a microaggregate within a macroaggregate.

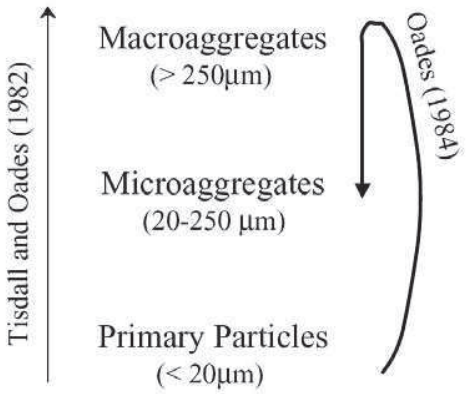


Figure II.11: The opposing chronology of the formation of the hierarchical aggregate orders implicitly described by Tisdall and Oades (1982) vs. postulated by Oades (1984).

Six *et al*. (1998) developed a conceptual model (Figure II.12) to explain the influence of disturbance (e.g. tillage) on soil C stabilization rates based on the feedback between POM and macro- and microaggregate dynamics and additional data collected in native grassland, no-tillage and conventional tillage agroecosystems.

This conceptual model of the 'life cycle' of a macroaggregate illustrates the formation of new microaggregates within macroaggregates and the accumulation vs. mineralization of aggregate-associated organic C. As aggregate turnover takes place an aggregate forms and stabilizes around particulate organic matter encrusted with microbial products and earthworm mucus, it becomes unstable due to a cessation of microbial activity and eventually disrupts. Disturbances such as tillage enhance macroaggregate turnover, which diminishes the formation of new microaggregates within macroaggregates and the protection of soil organic matter in these

microaggregates.

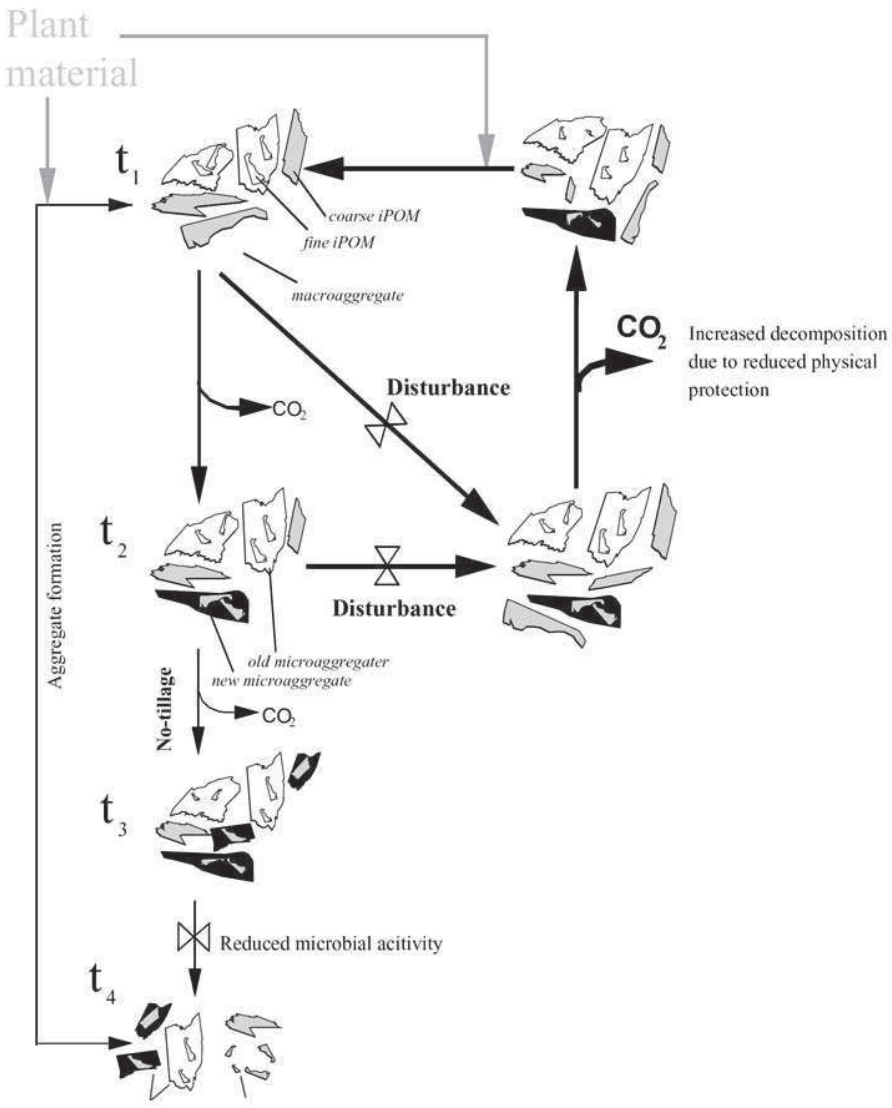


Figure II.12: The conceptual model of the 'life cycle' developed by Six et al., (1998). Figure is adopted from Six et al. (2000a).

Six *et al*. (2004) provided a review of research on soil aggregate formation and the role of five major factors (soil fauna, microorganisms, roots, inorganics, and physical processes) on soil aggregate dynamics. Major progress has been made in the understanding of the link between aggregates, soil biota and soil organic matter dynamics, but quantification of the single influences and involved feedback

mechanisms remain lacking. Promising solutions for this could be integrating aggregation measurements with morphological characterization and with 2D and 3D spatial information.

Six *et al*. (2004) pointed out the most important concepts constituting our current understanding:

(1) A hierarchical order of aggregates exists in soil where SOM is the major binding agent;

(2) Microaggregates are formed within macroaggregates;

(3) Root-derived POM plays an important role in aggregate dynamics;

(4) The activity of earthworms has a decisive role in the formation of macro- and microaggregates;

(5) SOM is predominantly stabilized in stable microaggregates; and

(6) Changes in the rate of macroaggregate turnover influence SOM stabilization across soil types and disturbance regimes.

We propose that the following factors directly influence soil aggregation: (1) soil fauna; (2) roots; (3) soil microorganisms; (4) organic matter; (5) inorganic binding agents and (6) environmental variables.

Aggregation of a given soil is an equilibrium among three complementary processes, formation (by biotic or abiotic mechanical agents), stabilization (by electrostatic attraction or glueing of particles by colloids) and disruption by mechanical agents and/or destruction of stabilizing chemical agents (Table Ⅱ.2; Figure Ⅱ.13).

Table Ⅱ.2: Soil structure in temperate soils: agents in structure formation and stabilization, processes involved, and scale of structure (Carter and Stewart, 1996)

Structure forming agent	Structure forming process	Scale of structure
Humic substances; hydroxides of Fe and Al; polyvalent metal cations (e.g. Ca); clays	Allow bonding between soil mineral and organic components	Microaggregation
Polysaccharides	Gelatinous glue; organo-mineral bonding	Micro- and macroaggregation
Plant roots; fungal hyphae	Enmesh soil aggregates; exude polysaccharides	Macroaggregation
Soil fauna (e.g. earthworms)	Mix organic matter with soil colloids; form large pore or gallery networks	Macroaggregation

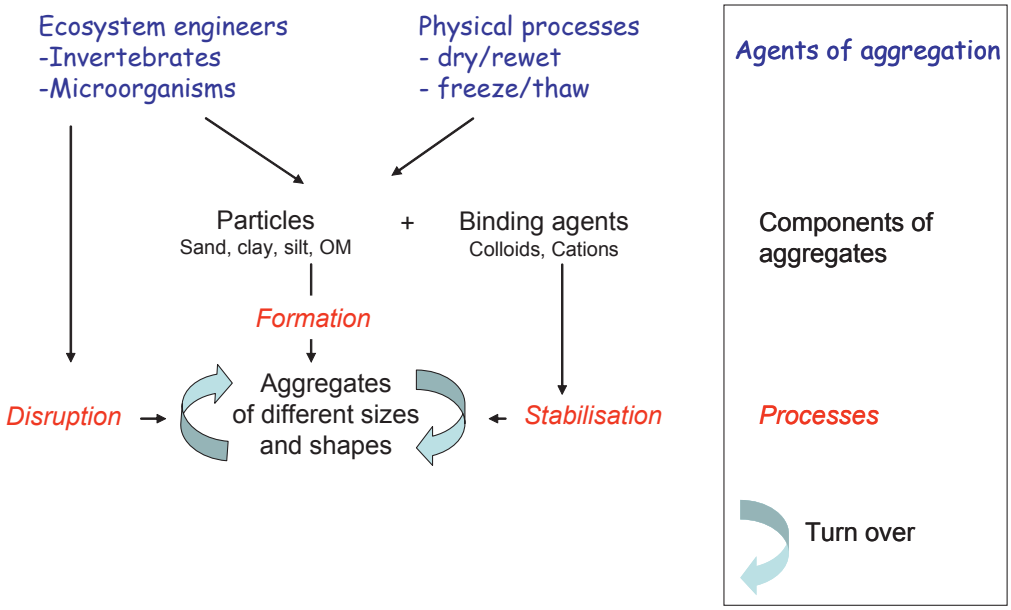


Figure Ⅱ.13: A general model of processes and agents involved in the formation of aggregates.

Aggregate formation

As shown in the model of Figure Ⅱ.13, aggregate formation requires the action of large organisms (invertebrates or roots) that organise particles into structures (e.g., earthworm cats, termite mounds, ant deposits…), create local compaction in soils (roots), or enclose particles into networks that maintain them together (fungal hyphae). Physical processes such as freeze-thaw cycles and dry-wet cycles can also create macroaggregates in soils (Edwards, 1991; Denef *et al*., 2001).

Soil macro fauna that influence soil aggregation are mainly earthworms, termites and ants, although Coleoptera, Isopods and Myriapods and even some vertebrates may occasionally play a role.

In soils that have no active ecosystem engineers, aggregation by microorganisms may become a predominant process (Plante and McGill, 2002; De Gryze S *et al*., 2005). These aggregates, however, tend to have much shorter life spans than equivalent size aggregates made by invertebrates and they are less stable.

Root-related processes affecting soil structure can be grouped into five categories:

(1) root penetration; (2) changed soil water regime; (3) root exudation; (4) dead root

decomposition; and (5) root entanglement (Angers and Caron, 1998).

Stabilization of aggregates

Microbial activity participates in aggregate stabilization through the production of mucilages that stick particles together and inclusion of particles into networks of fungal hyphae. The contribution of microbial activity to aggregate formation, stabilization and eventually degradation has been extensively reviewed (Degens, 1997). The link between microorganisms and aggregation is pertinent, microbial biomass and water-extractable carbohydrates have been found correlated to varying degrees with aggregation (Degens, 1997). The fungal mycelium and the production of mucilages by bacteria and fungi cement particles together to form aggregates of different sizes (Oades and Waters, 1991; Oades, 1993).

Oxides and Calcium also participate in the stabilization of aggregates made by organisms or physical processes as inorganic binding agents. Cations such as Si^{4+}, Fe^{3+}, Al^{3+} and Ca^{2+} stimulate the precipitation of compounds that act as bonding agents for primary particles. Long-term stability of aggregates is actually often related to the presence of recalcitrant C (CR) compounds and metal ions that maintain the electrostatic links created at the formation of the aggregates (Six *et al*., 2000b).

Dynamics of aggregate formation

Aggregate stability tests have been developed to assess soil quality, aggregates greater than 0.25 mm are classified as macroaggregates; they are more vulnerable to soil management practices than microaggregates, <0.25 mm (Tisdall, 1996). Within the macroaggregate size range, the 1-2 mm size fraction is commonly used to determined aggregate stability (Kemper and Rosenau, 1986; Angers and Mehuys, 1993; Arshad *et al.*, 1996). However, Gijsman (1996) has shown greater sensitivity to management-induced treatment differences by determining the stability of a larger size range of macroaggregates (0.25–2.0 mm). For greater sensitivity and ease of use, our proposed method determines the percentage of water-stable macroaggregates in the 0.25–2.0 mm size range, corrected for sand (0.25 mm).

Ⅱ.3.2 Methods to assess soil aggregate size distribution and stability

Several methods have been proposed to determine soil aggregate-size distribution and stability. The suitability of these methods depends on the purpose of the study.

A frequently used wet-sieving test is the single-sieve method proposed by Kemper and Koch (1966), and later modified by Kemper and Rosenau (1986). In this method, cyclically submerging and sieving soil in water simulates the natural stresses involved in the entry of water into soil aggregates. Soil samples were collected from the 0–7.6 cm depth and allowed to air-dry 48 h if they were moist. The samples were gently passed through a 2 mm sieve to remove gravel. The amount of soil or loading rate on the sieve can affect the amount that falls through during the wet-sieving process. Beare and Bruce (1993) reported that a loading rate of 0.66 g cm^{-2} gave reproducible results.

The single-sieve standard method (Kemper and Rosenau, 1986) uses a loading rate of 0.40 g cm^{-2}. Seybold and Herrick (2001) used a loading rate of 0.51 g cm^{-2}. The higher loading rate was chosen to increase the amount of soil analyzed and improve ease of measurement by the user. Lower loading rates can be used, but it must be consistent throughout the measurements. Kemper and Rosenau (1986) used 36 cycles per minute for 3 min through a vertical distance of 1.3 cm.

Two different pre treatments of aggregates: capillary wetting or slaking can be implemented with this method.

Ⅱ.3.3 Wet-sieving method utilised in our study

Soil samples were taken from the corners and center of each site, manual separated into big clods and then air-dried. Samples were passed through a set of sieves with diameters 5 mm, 3 mm, 2 mm, 1 mm and 0.5 mm mesh, soil retained on each sieve was weighed. Two 80 g sub-samples of air-dried soil were composed according to original aggregate percent (dry sieved) for wet-sieving analysis.

We designed a machine according to the practice of Seybold and Herrick (2001, Photo Ⅱ.1).

Pretreatments were applied before wet sieving: soil samples were saturated in deionized water (Kemper and Rosenau, 1986) with rapid immersion for 30 minutes. Soil was then transferred to a set of sieves with respective diameters of 2 mm, 1 mm, 0.5 mm, 0.25 mm and 0.053 mm mesh.

Photo Ⅱ.1: The Wet-sieving apparatus used in our experiment.

The tackle box was moved up and down in the water through a vertical distance of about 5 cm at the rate of 40 cycles per minute. Care was taken to make sure the aggregates remained immersed in water on the upstroke. Samples were then sieved for 15 min, aggregates were physically separated in six aggregate-size fractions: (i) large macroaggregates > 2000 μm in diameter, (ii) small macroaggregates between 1000 and 2000 μm in diameter (iii) small macroaggregates between 500 and 1000 μm in diameter, (iv) small macroaggregates between 250 and 500 μm in diameter (v) microaggregates between 53 and 250 μm in diameter, and (vi) the fine fraction < 53 μm in diameter.

The material retained on each sieve was carefully removed into a box with water and oven dried at 60 ◦C for 24 h. After drying, the weight of each box plus aggregates was recorded (Figure Ⅱ.14).

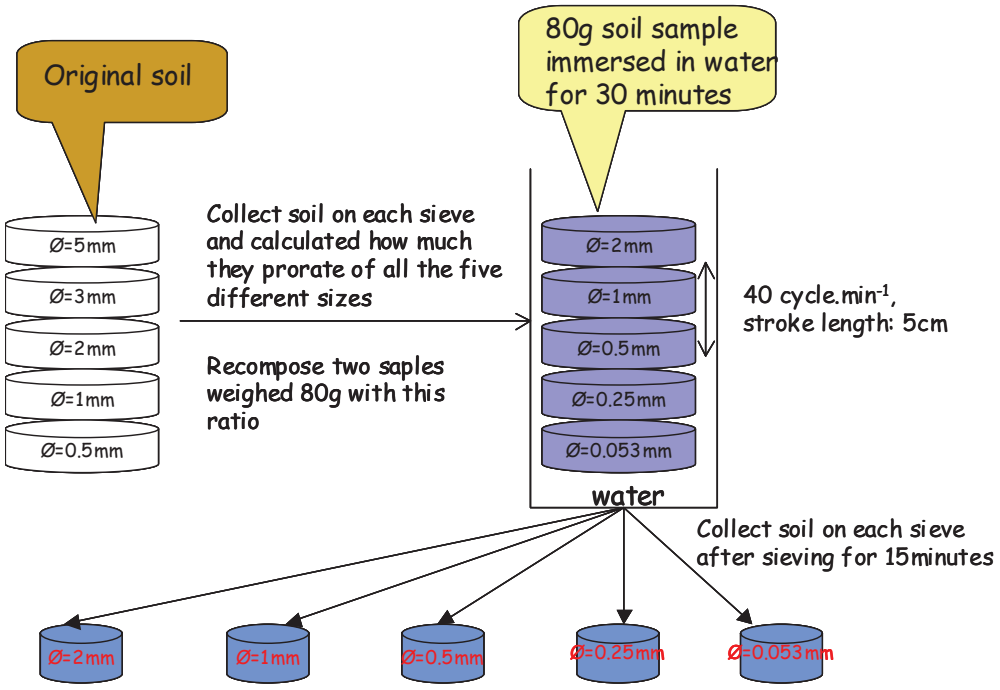


Figure II.14: Experimental procedure used to assess aggregate stability.

Sand particles may be weighed as aggregates of the same class size and an adequate correction is needed.

Sand content of each aggregate-size fraction was determined by weighing the material that was retained on the sieve with a 53µm screen after dispersal of the aggregates with sodium hexametaphosphate (5 g $L^{-1)}$. Sand correction was done as required.

Measuring Aggregation indices

Soil aggregation may be determined by mean weight diameter (MWD), geometric mean weight diameter (GMD) and aggregate stability (AS, %) index, which are obtained by fractioning the soil material into aggregate classes by wet sieving (van Bavel, 1949; Kemper and Chepil, 1965). More complex metrics such as the aggregation index and the normalized stability index were searched recently (USDA, 1998; van Steenbergen *et al.*, 1991; Six *et al.*, 2000a) (Table II .3). Geometric mean diameter (GMD) is an index that characterizes the structure of the

whole soil by integrating the aggregate size class distribution into a single number, which gives information of aggregates distribution.

In our study, we used GMD to indicate soil aggregate stability distribution. It was calculated as follows:

$$\mathrm{GMD} = \exp\left\{\frac{\sum w_i \ln x_i}{\sum w_i}\right\}$$

Where *wi* is the weight of the aggregates of each size class (g) and ln *xi* the natural logarithm of the mean diameter of size classes.

Table II.3: Summary of indices proposed for quantitatively assessing soil aggregate stability. n is the total number of aggregate size classes (Marquez et al., 2004).

Index	Reference/Comments
Mean Weight Diameter: $MWD = \sum_{i=1}^{n} \overline{x}_i w_i$	**van Bavel (1949)** Easy to calculate (see the geometric mean diameter index for variables definition).
Geometric Mean Diameter: $GMD = \exp\left[\sum_{i=1}^{n} w_i \log(\overline{x}_i) \Big/ \sum_{i=1}^{n} w_i\right]$	**Mazurak (1950)** $\overline{x}_i$ is the mean diameter of each size fraction. w_i is the proportion of the total sample weight occurring in the size fraction i. Extensive calculations.
Water Stable Aggregates: $WSA(\%\ \text{of soil} > 250\ \mu m) = \frac{\text{weight of dry aggregates} - \text{sand})}{(\text{weight of dry soil} - \text{sand})} \times 100$	**Kemper (1966) and USDA (1998)** Useful when $G_2 = 0$; there are not stable small macroaggregates that can result from the fragmentation of unstable large macroaggregates upon slaking.
Aggregation Index: $AI = 100 - DI$ **Disruption Index:** $DI = \frac{DV}{DV_{max}}$ $DV_{max} = \frac{1}{n}\sum_{i=1}^{n} i\ DVS_{max}$ and $DV = \frac{1}{n}\sum_{i=1}^{n} i\ DVS_i$ $DVS_i = \frac{[(PW_i - PW_{io}) + \lvert PW_i - PW_{io}\rvert]}{2\left(100 - \sum_{j=i+1}^{n} PW_{jo}\right)}$	**van Steenbergen et al. (1991)** Slaked and capillary-wetted pretreatments. Only gains are used. Normalization with respect to the maximum disruption level possible. $i = 1$ for the largest size class. PW_i and PW_{io} are the proportion of total sample weight in size class i upon slaking and capillary-wetting, respectively. DVS_{max} is the absolute maximum disruption value for size class i.
Normalized Stability Index: $NSI = 1 - \left(\frac{DL}{DL_{max}}\right)$ and $DL = \frac{1}{n}\sum_{i=1}^{n}[(n+1) - i]\ DLS_i$ $DLS_i = \frac{\{[(P_{io} - S_{io}) - (P_i - S_i)] + \lvert(P_{io} - S_{io}) - (P_i - S_i)\rvert\}}{2(P_{io} - S_{io})}$ $DL_{max} = \frac{1}{n}\sum_{i=1}^{n}[(n+1) - i]\ DLS_i\ (max)$ $DLS_i\ (max) = \frac{[(P_{io} - P_p) + \lvert(P_{io} - P_p)\rvert]}{2(P_{io} - S_{io})}$	**Six et al. (2000)** Slaked and capillary-wetted pretreatments. Correction for the aggregate-sized sand content. Normalization with respect to the maximum disruption level possible. Based on weight losses. $i = 1$ for the smallest size class. P_i and P_{io} are the proportion of total sample weight in size class i upon slaking and capillary-wetting, respectively. S_i and S_{io} are the proportions of sand with size i in aggregates of size i upon slaking and capillary wetting, respectively. P_p primary sand particle content with the same size as the aggregates size class after complete disruption of the whole soil.

Ⅱ.3.4 Results and discussion

Ⅱ.3.4.1 Aggregation in the 0-10 cm soil layer

Two sub-samples from depth of 0-10 cm for each point were analysed by wet-sieving method, water-stable aggregate distribution and geometrical diameter was calculated (Annexe, Table 12; Figure Ⅱ.15).

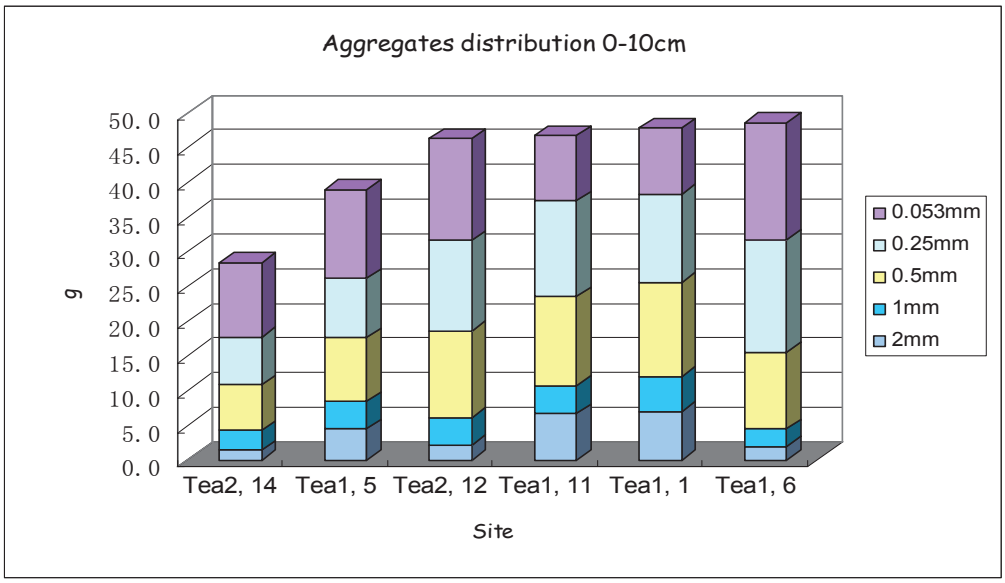


Figure Ⅱ.15: Variation of aggregate distribution for samples taken from 0-10 cm among the 6 sites (means of two repetitions).

Tea1, 6 had the highest total amount of aggregates and highest amount of aggregates with diameter between 250µm and 53µm; the minimum total amount of aggregates was found in Tea2, 14. Tea1, 1 and Tea1, 11 had highest total amount of aggregates that diameter > 250 µm. Difference of GMD for samples taken from 0-10 cm among the 6 sites was significant ($F = 5.20$, $p = 0.0022$).

Principal Component Analysis showed significant differences among the different sites. Axis 1 was determined by the amount of large aggregates > 0.5 mm whereas smaller aggregates (< 0.5 mm) determined axis 2 (Figure Ⅱ.16).

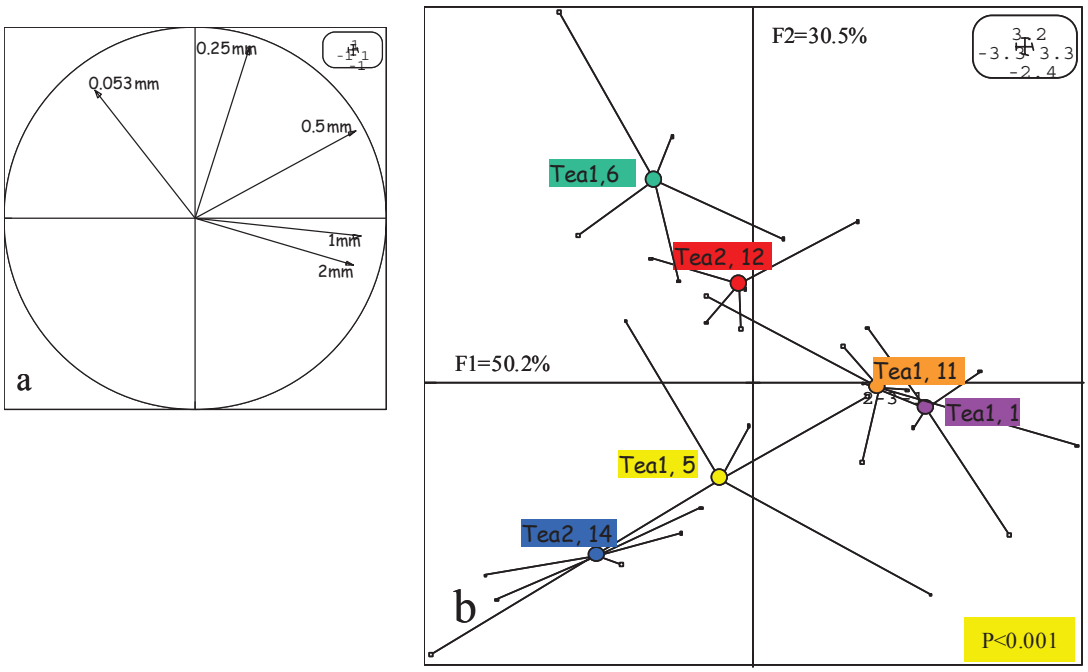


Figure II.16: Ordination of sites by PCA analysis of different aggregate diameters.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 5 aggregate diameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together 80.7% of the inertia.

Axis 1 of the PCA (50.2% variance explained) opposed sites Tea1, 1 and 11 with large proportions of macroaggregates of 1 mm and 2 mm to others. In site Tea1, 1 soil comprised 7.0% and 5.0% respectively of 2 mm and 1 mm aggregate; at site Tea1, 11 respective values were 6.6% and 4.1%, still higher than at the other 4 sites; axis 2 (30.5% variance explained) opposed sites Tea1, 6 and Tea2, 12 to the other 4 sites, that had less microaggegates < 0.5 mm; at site Tea1, 6 aggregates < 0.053 mm comprised aggregate 16.9% of soil, the highest value recorded among the 6 sites.

A co-inercia analyses, not shown here, among soil variables in both soil layers and aggregation parameters including the GMD measured from stable aggregate measurements, was close to significant (RV=0.08; $p<0.10$). The analysis showed that the occurence of large aggregates was linked to C and clay contents; smallest aggregates were specially linked to clay contents that also determined largely axis 2.

A second co-inercia analysis that only considered aggregate classes and not GMD was highly significant (RV=0.27; p<0.02). The improvement in significance in the late analysis after removal of GMD reflects the fact that GMD summarises data for large aggregates that define Axis 1 and data on micro aggregates that define axis 2.

This justifies our doing another multivariate PCA analysis to seek a relationship between GMD and other soil parameters.

Correlation circle of variables showed GMD has a strong positively correlative to clay and soil total C on axis 1, Factor 1 mainly related soil properties such as clay content and total C too and soil aggregate stability summarised in GMD. Soil properties connected with microbial activity (soil respiration, microbial biomass C) separated sites along axis 2 (Figure Ⅱ.17).

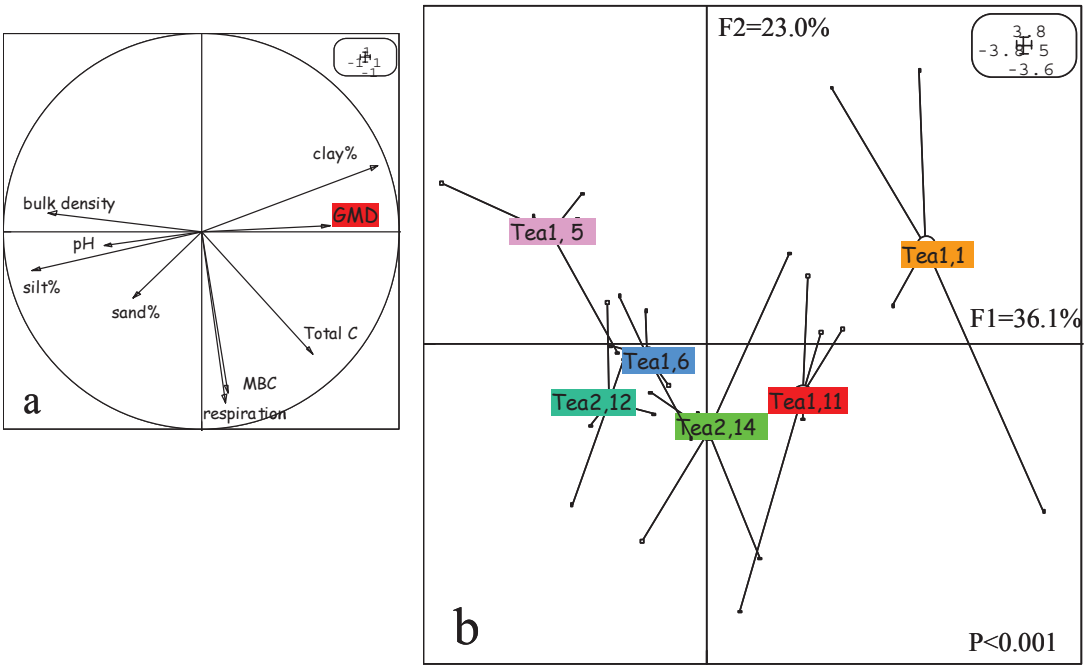


Figure Ⅱ.17: Ordination of site by PCA analysis of basic physical, chemical, soil organic matter properties and GMD.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 9 parameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions), MBC: Microbial Biomass C.
P: probability for separation among groups was significant. Factors 1 and 2 explain together 59.1% of the inertia.

Axis 1 of the PCA (36.1% variance explained) opposed sites Tea1, 1 and 11 to other sites; axis 2 (30.5% variance explained) opposed sites Tea1, 1 and Tea1, 5 to the other 4 sites. Site Tea1, 1 had the highest clay content (55.1%) and highest GMD value (0.562 mm), poor soil respiration status (respiration = 0.0197 mol CO_2 kg^{-1}), Tea1, 5 had higher GMD (0.5403 mm) and the highest bulk density (1.27 g cm^{-3}), and poor soil carbon status (Total C = 13.11 g kg^{-1}, MBC = 204.84 mg kg^{-1}) compared with the sites Tea1, 11, Tea2, 14 and Tea2, 12.

Ⅱ.3.4.2 Aggregation in the 10-20 cm soil layer

Two sub-samples from depth of 10-20 cm for each point were analysed by wet-sieving method, water-stable aggregate distribution and geometrical diameter was calculated (Annexe, Table 13; Figure Ⅱ.18).

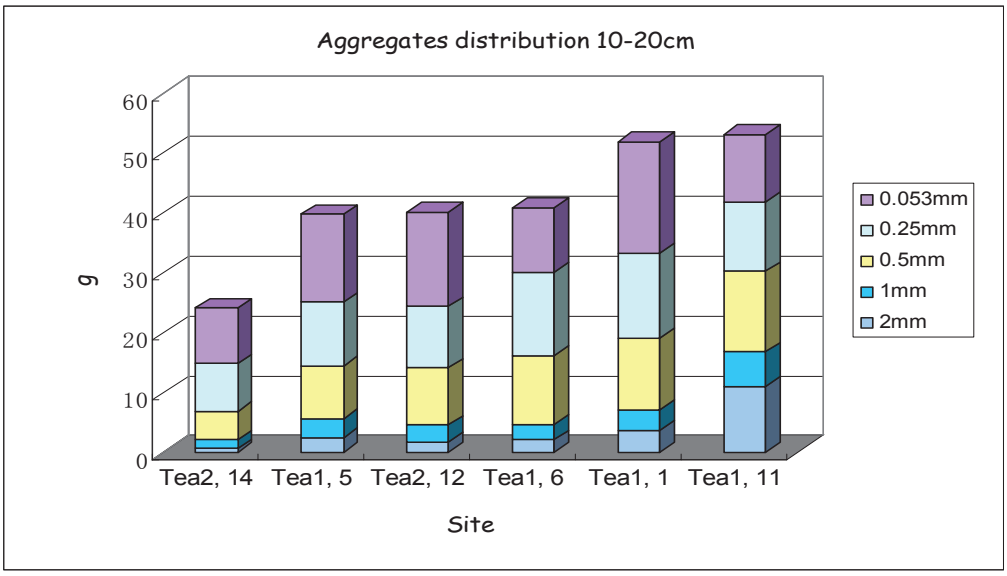


Figure Ⅱ.18: Variation of aggregate distribution for samples taken from 10-20 cm among the 6 sites (means of two repetitions).

Tea1, 11 had the largest total amount of aggregates and highest total amount of macroaggregate with diameter > 250 µm; the minimum total amount was found in Tea2, 14. The largest amount of aggregates with diameter between 250 µm and 53µm was found in Tea1, 1. Difference of GMD for samples taken from depth of 10-20 cm among

the 6 sites was significant (F=5.61, p=0.0015).

Principal Component Analysis showed significant differences among the different sites. Large aggregates were significantly linked to axis 1 while axis 2 had high correlation with smallest aggregates (Figure Ⅱ.19).

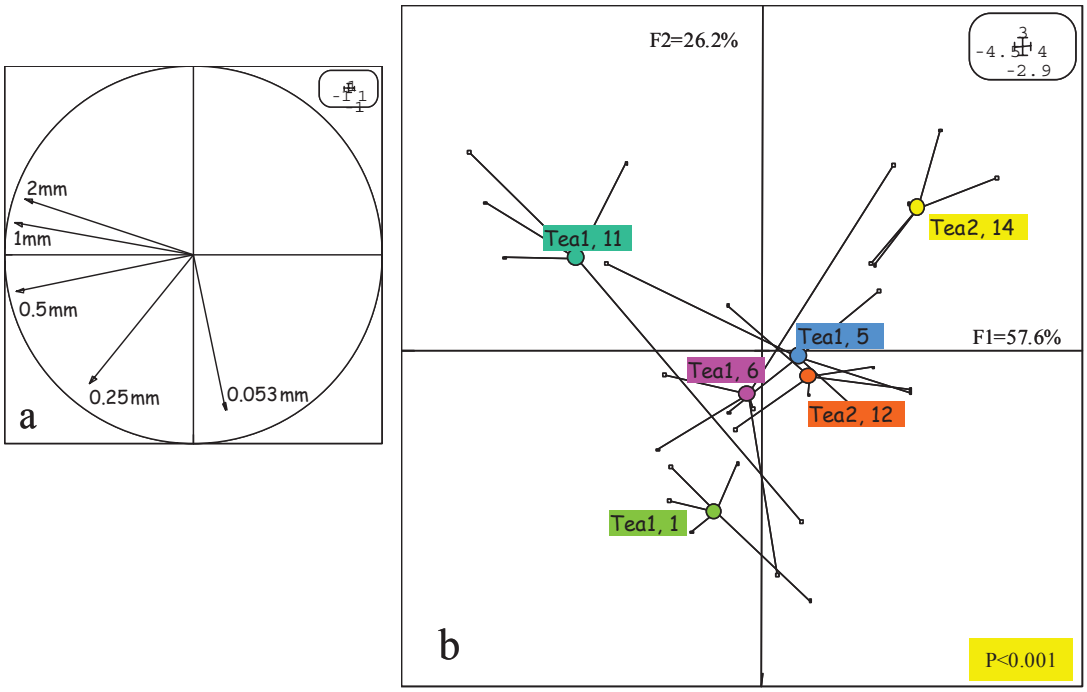


Figure Ⅱ.19: Ordination of sites by PCA analysis of different aggregate diameters.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 5 aggregate diameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together 83.8% of the inertia.

Axis 1 of the PCA (57.6% variance explained) opposed sites Tea1, 11, Tea1, 1 and Tea1, 6 with more macroagregates to others, site Tea1, 11 had the 11.1% and 5.8% of 2 mm and 1 mm aggregate; axis 2 (26.2% variance explained) opposed sites Tea1, 1 and Tea2, 12 to sites Tea1, 11 and Tea2, 14, with more aggregates with diameter < 0.05 mm, site Tea1, 1 and Tea2, 14 had a higher 5 mm aggregate percent of 18.6% and 15.8% separately.

Correlation circle of variables showed GMD is strong positively correlative to soil total C, MBC and soil respiration on axis 1. These soil properties connected with carbon together with soil texture separate sites on axis 2 (Figure Ⅱ.20).

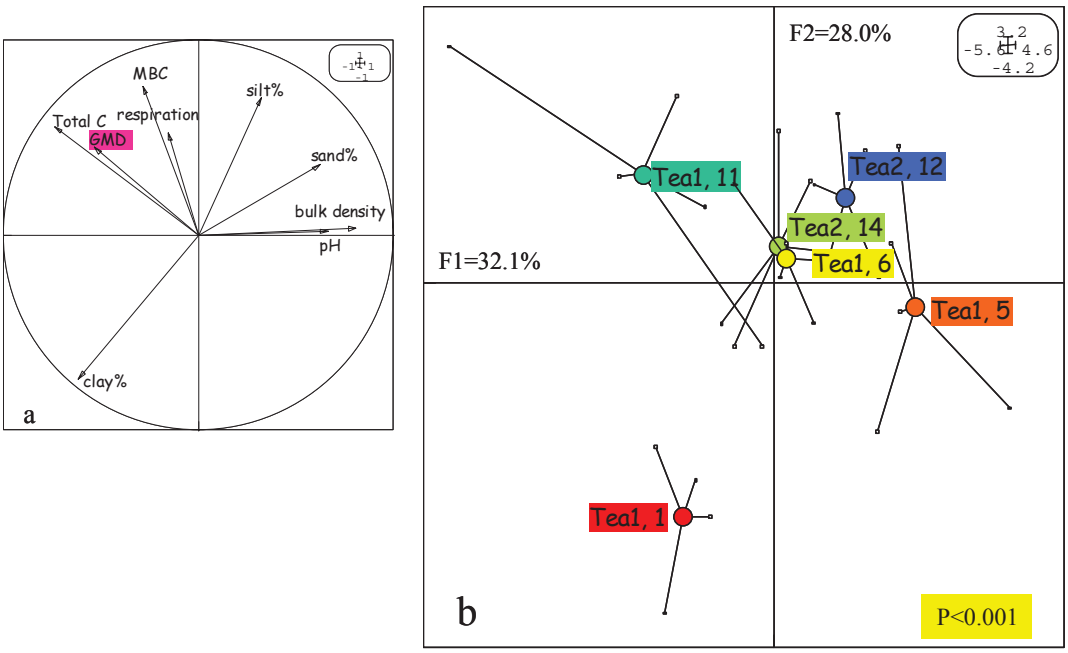


Figure Ⅱ.20: Ordination of site by PCA analysis of basic physical, chemical, soil organic matter properties and GMD.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 9 parameters.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions), MBC: Microbial Biomass C.
P: probability for separation among groups was significant. Factors 1 and 2 explain together 60.1% of the inertia.

Axis 1 of the PCA (32.1% variance explained) opposed sites Tea1, 1 and Tea1, 11 to other sites; axis 2 (28.0% variance explained) opposed sites Tea1, 1 and Tea1, 5 to the other 4 sites. The result was similar compared with this analysis for soil samples taken from 0-10 cm layer. Site Tea1, 1 had the highest clay content (57.3%), GMD value (0.392 mm) was much lower than value of 0-10 cm (0.562 mm), poor soil respiration status too (MBC = 85.45 mg kg^{-1}, Total C=14.84 g kg^{-1}, respiration=0.0145 mol CO_2 kg^{-1}), Tea1, 5

had the highest bulk density value (1.41 g cm^{-3}) and highest pH (5.02), compared with the sites.

Among soil samples taken from 0-10 cm, Tea1, 6 had the lowest GMD, the highest GMD was found in Tea1, 1. Among soil samples taken from 10-20 cm, Tea2, 14 and Tea1, 11 had the lowest and highest GMD respectively (Table Ⅱ.4; Figure Ⅱ.21).

Table Ⅱ.4: Average geometrical diameter of the 6 studied sites and their fertilizer application.

Sites	0-10 cm	10-20 cm	Description
Tea1, 1	0.562	0.392	20 years, chemical fertilizer
Tea1, 5	0.449	0.385	Replanted 2 years ago, chemical fertilizer and manure
Tea1, 6	0.368	0.427	20 years, chemical fertilizer and manure
Tea1, 11	0.540	0.618	15 years, chemical fertilizer and manure
Tea2, 12	0.409	0.367	Nearly 30 years, manure of chicken and cow
Tea2, 14	0.385	0.341	Nearly 30 years, urea and spray fertilizer for leaves

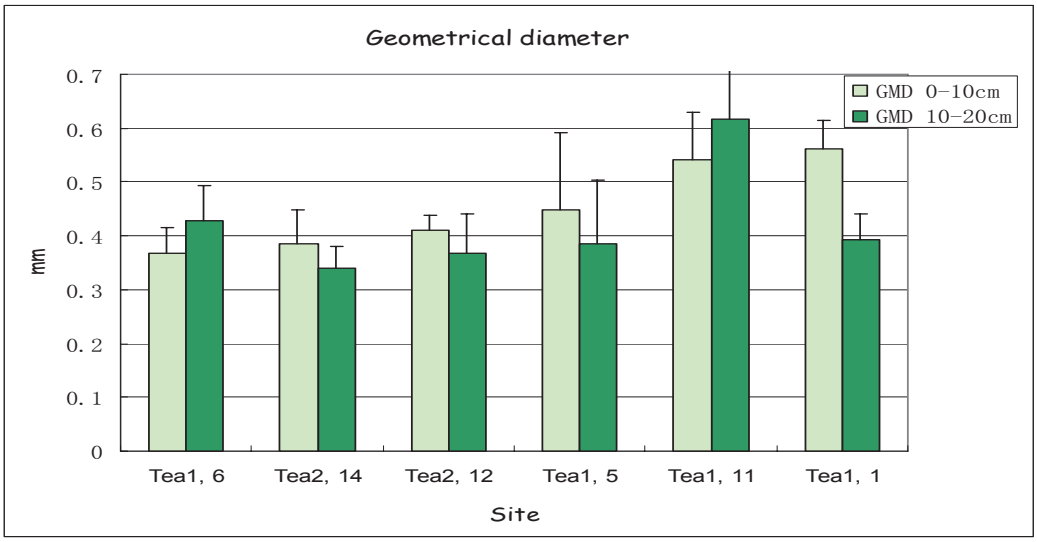


Figure Ⅱ.21: Variation of geometrical diameter among the 6 studied sites.

Ⅱ.3.5 Near infrared reflectance spectroscopy (NIRS)

Near Infrared Spectrometry has been widely used during the last three decades in the assessment of the moisture content of seeds (Ben-Gera and Norris, 1968), C, N and P contents in plant material (Gillon et. al, 1999) and soil properties (chang et. al, 2001; Velasquez et. al, 2005) and other domains.

Shepherd and Walsh (2002) developed a scheme that makes it possible to use a library of spectra of soils from eastern and southern Africa to estimate such soil properties as Ca, Mg, K and exchangeable P, organic C, pH, potential of mineralization of N, effective cation exchange capacity, and particle size and distribution, based on diffuse reflectance spectroscopy analysis.

Velasquez *et al* (2005) have shown recently the great capacity of this technique to discriminate soils according to their quality.

Soil water stable aggregates collected on meshes 0.5 mm, 0.25 mm and 0.053 mm (samples collected at 2 mm, 1 mm were not enough for NIRS analysis) were grinded at 0.002 mm for NIRS analysis, same parameters were chosen as Velasquez *et al* (2005) (Figure Ⅱ.22)

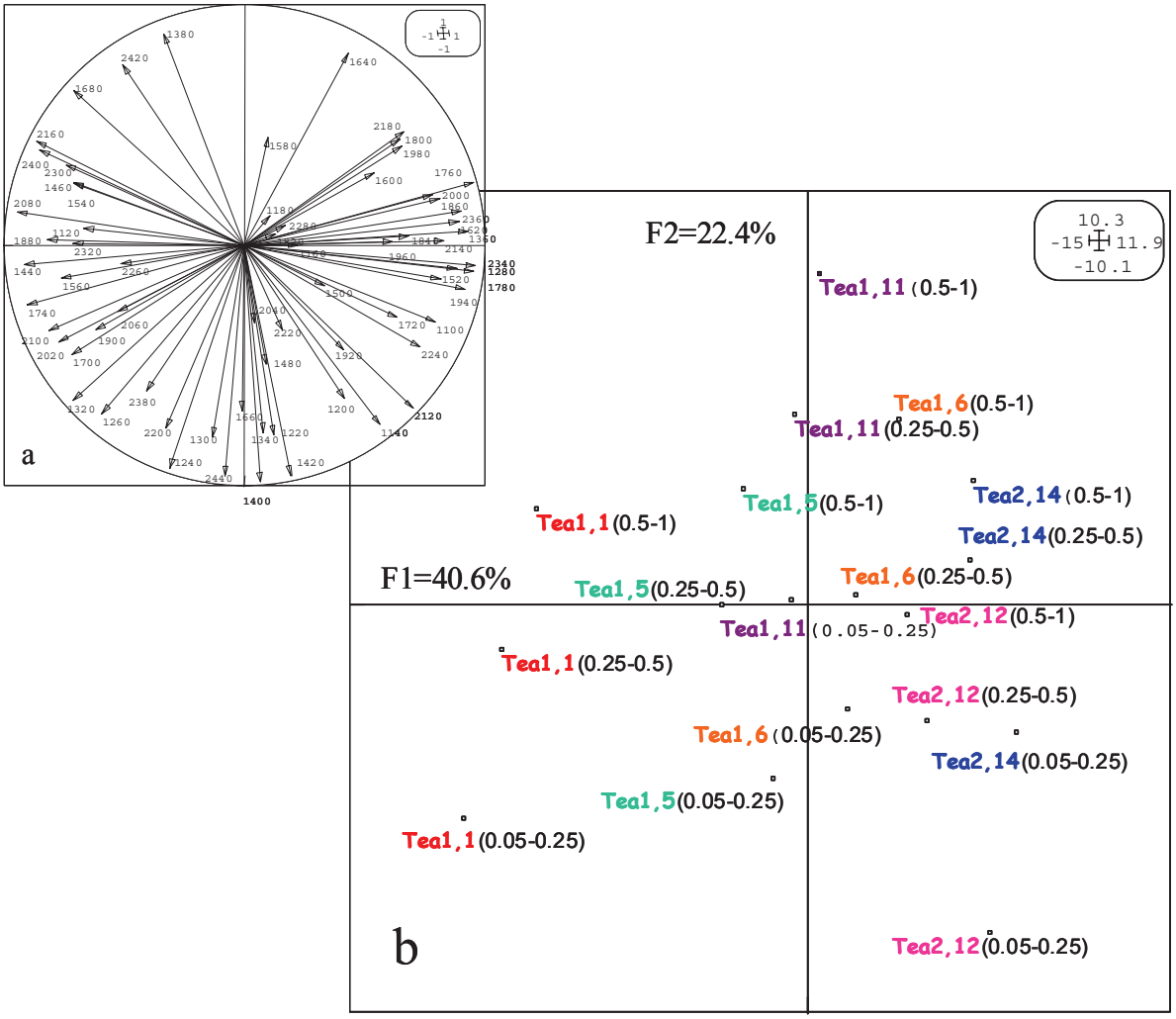


Figure II.22: Result of soil NIRS analysis. Projection of aggregates of different diameters in factorial space defined by PCA analysis of different wave length (samples taken from 0-10cm). 0.5-1 was aggregate which diameter between 0.5 and 1 mm, 0.25-0.5 was aggregate which diameter between 0.25 and 0.5 mm, 0.05-0.25 was aggregate which diameter between 0.05 and 0.25 mm.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis, with wave lengthes from 1100 nm to 2440 nm, granularity was 20 nm.
(b) Projection of aggregates with different diameters form the 6 sites in the plane defined by factors 1 and 2.

Factors 1 and 2 explain together 63.0% of the inertia. Factor 1 clearly expressed significant signatures of soil organic matter from the different sites. Sites from the Tea 2 group have highest coordinates on the axis, in relation with their higher organic contents.

Factor 2 classifies aggregates according to size classes. Most aggregates of the

largest size classes project on the positive side of the axis while the smallest ones project on the negative side.

These results confirm the ability of NIRS to discriminate aggregates according to their nature. In further studies of soil aggregation dynamics this approach will be very useful at tracing organic matter among aggregate classes in experiments.

Ⅱ.4 Soil morphology properties

Ⅱ.4.1 Basic concept of soil morphology and micromorphology

There are different emerging levels of soil structures in agricultural system, from primary scales in μm, secondary structure scales in μm to mm, tertiary structure scales in mm-cm and soil profiles in cm-m (Lavelle *et al.*, 2004b; Lavelle *et al.*, 2006) (Table Ⅱ.5; Figure Ⅱ.23). Macro- and micro-morphology propose different methods to study soil structure at different scales.

Field soil macro-morphology studies the succession and organization of soil horizons at the scale of profiles and soil catenas (Jongmans *et al.*, 2003).

Soil micromorphology is based on the analysis of thin sections prepared from undisturbed blocks of soil. Thin sections (30μm thick) are prepared and then divided into apparently homogeneous areas of interest further assigned to soil horizons using the field profile descriptions and thin section evidence. For each horizon, soil structure, void space, characteristics of the fine material and of larger organic and/or mineral features are recorded. The presence of roots, plant fragments, lignified materials, charcoal, sclerotia, fruiting bodies, mycorrhiza, fungal spores, phytoliths and mineral and rock fragments were also noted. An emerging soil tertiary structure, with increasing structural and functional complexity, can influence soil physical and biological processes and consequently influences a wide range of soil functions (Table Ⅱ.5).

In studies based on this technique, Pulleman *et al.* (2005) distinguished two classes of biogenic macroaggregates (fresh casts and welded casts), one class of physicogenic macroaggregates (angular to subangular blocky macroaggregates) and an intermediate fraction (rounded to subrounded macroaggregates). The structural arrangement of mineral particles and organic matter and the quantitative contribution of particulate organic matter (POM) and microaggregates were studied in thin sections. Comparison of the different macroaggregate types in thin sections revealed that the worm-made macroaggregates of the permanent pasture soil were considerably enriched in fine POM and microaggregates, in which large amounts of organic matter were intimately mixed with fine mineral material. By contrast, worm casts of the conventional arable field and an organic arable field soils were hardly enriched in POM and microaggregates.

Table II.5: Emerging levels of soil structural and functional complexity in agricultural systems.

Soil structural entities and components	Soil functional features and processes
Primary structure (scale in μm)	
Mineral–organic matter complexes	Modification of microenvironment
Uncomplexed organic matter	Surface reactivity
Microaggregates (2–250 μm diameter)	Chemical stabilization of organic matter
Secondary structure (scale in μm–mm)	
Aggregated mineral-organo complexes	Physical protection of organic matter
Uncomplexed organic matter	Soil porosity and aeration
Macroaggregates (>250 μm diameter)	Pore space and continuity
Fine roots	Microfaunal habitat
Fungal hyphae	Water retention
Tertiary structure (scale in mm–cm)	
Whole, intact soil *in situ*	Macrofauna and bioturbation
Macropores and large roots	Pore continuity and preferential flow
Macrostructure	Leaching and gaseous emissions
	Compaction and draft
Soil profile (scale in cm–m)	
Soil peds (granular, blocky, platy, columnar)	Soil disturbance and movement
	Abiotic features (freeze–thaw; shrink–swell)
Clods	Tillage impacts on structure

Christensen (2001) and Carter et al. (2004)

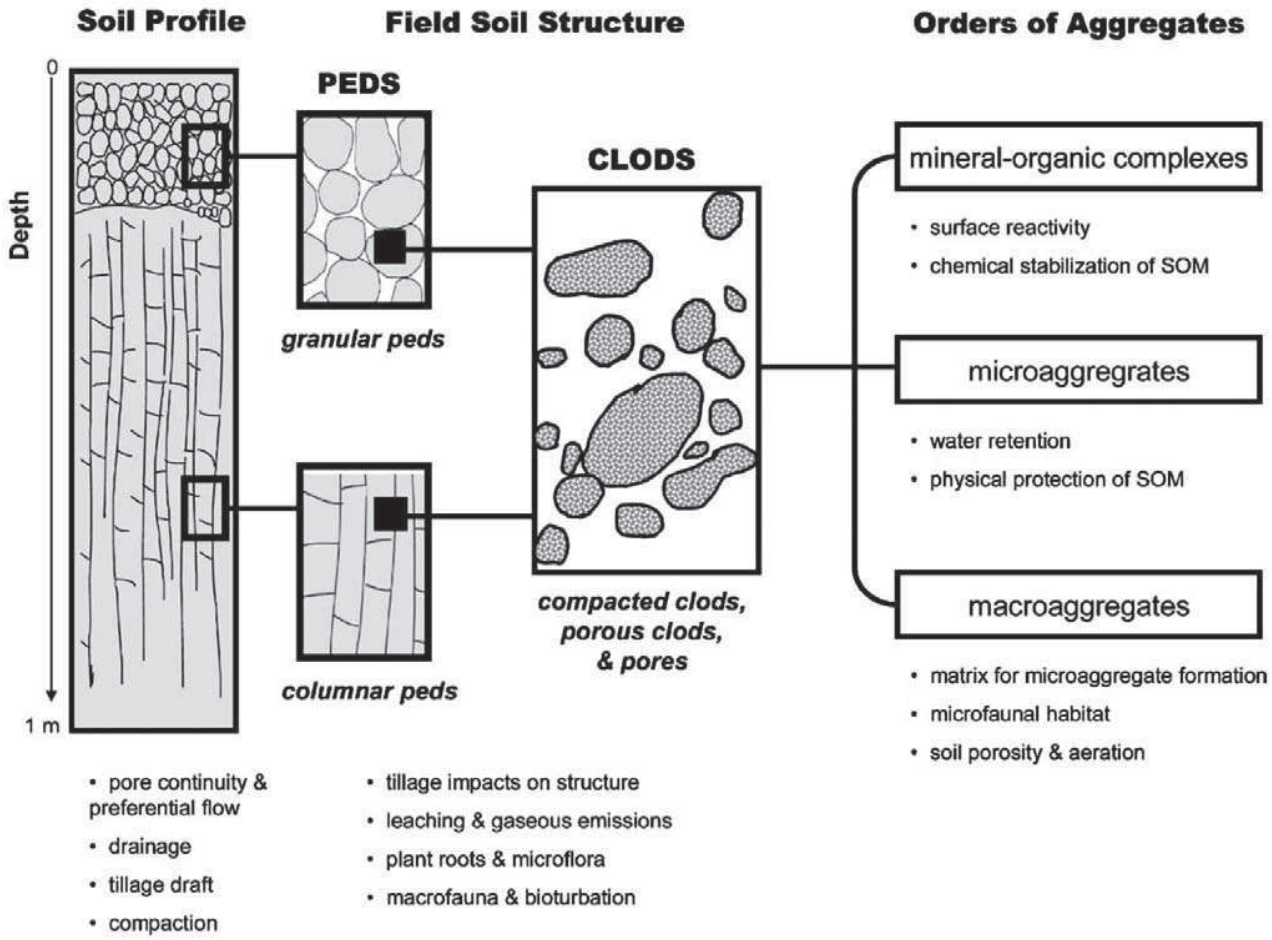


Figure II.23: Soil structure, including soil architecture, over several orders of magnitude (<µm to >cm) from soil profile in the field to microscopic level along with some related soil processes and conditions (Carter, 2004).

As Figure Ⅱ.20 demonstrates, soil structural components range over several orders of magnitude (from < μm to > cm) from the soil pro- file with ped or clod morphology to the formation of nascent aggregates in the rhizosphere, with each level influencing specific soil processes.

Topoliantz *et al.* (2000) proposed an intermediate approach for "small volume" structure of soil (Figure Ⅱ.24). Quantitative analyses of these morphological features provided information about soil compaction, earthworm and enchytraeid activity and distribution of roots and crop residues in the soil matrix.

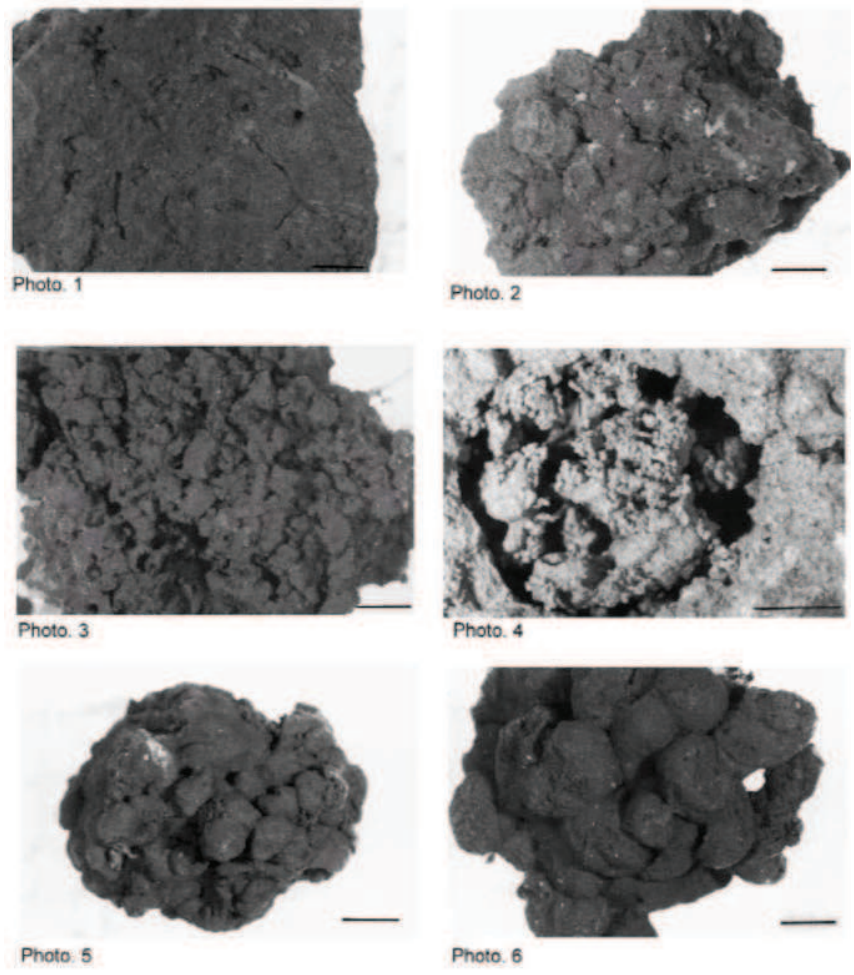


Figure Ⅱ.24: Photographs of some components of the soil matrix in topsoil profiles (Topoliantz et al., 2000).

Ⅱ.4.2 Results and discussion

We used the method described in I.7.2 to evaluate the state of aggregation of the soil in different sites. In this study, 13 items were studied as soil morphological properties (TableⅡ.6).

Table Ⅱ.6: 13 visual components of soil morphology

1	BA l	Large biogenic aggregate
2	BA m	Medium size biogenic aggregate
3	BA s	Small biogenic aggregate
4	PA l	Large physical aggregate
5	PA m	Medium size physical aggregate
6	PA s	Small physical aggregate
7	Roots	Roots
8	Stones	Stones
9	Woods	Woods
10	Stems	Stems
11	Seeds	Seeds
12	Leaves	Leaves
13	Inver	Invertebrates

Ⅱ.4.2.1 Variation of soil morphological composition

Soil morphological items exhibited large variations across the 20 sites (Annexe, Table 14; FigureⅡ.25).

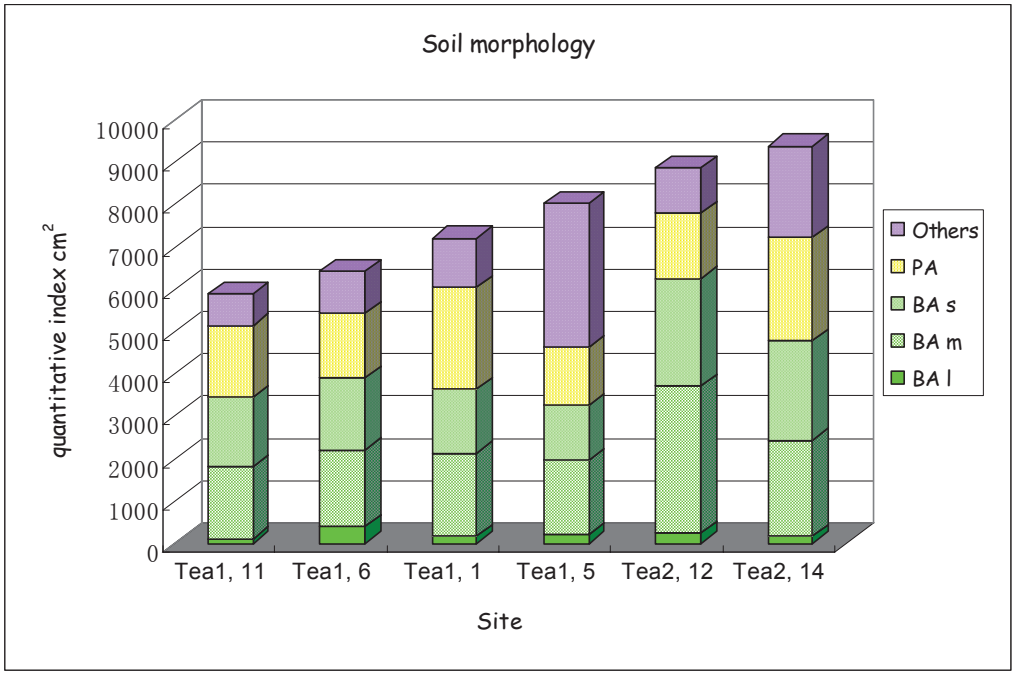


Figure Ⅱ.25: Variation of soil morphological composition among the 6 studied sites.

Tea2, 14 had the maximum amount of all morphological items; maximum amount of biogenic aggregates was found in Tea2, 12. Two sites in Tea2 had obviously higher biogenic aggregates than sites in Tea1. Large quantity of stones was found in Tea1, 5 and Tea2, 14.

Ⅱ.4.2.2 Multivariate analyses (PCA) for soil morphology in the 6 studied sites

Factor 1clearly separated sites according to biogenic and physical aggregates; factor 2 separated sites according to aggregate and leaves, stems and woods. Biogenic aggregates were correlated with invertebrate, it showed the invertebrates had a obvious influences on soil structure which created biogenic aggregates and their faecal pellets composed biogenic aggregates (Figure Ⅱ.26).

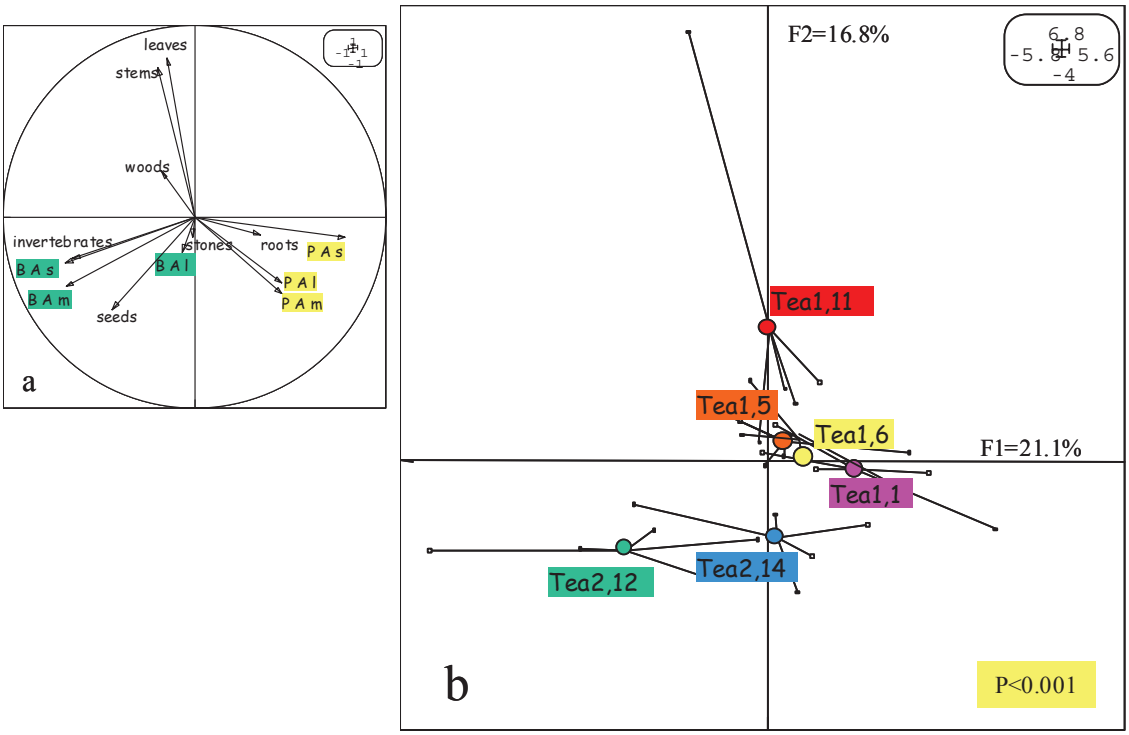


Figure Ⅱ.26: Ordination of sites by PCA analysis of 13 soil morphology components.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 13 soil morphology components.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. The six tea blocks could be separated significantly. Factors 1 and 2 explain together 37.9% of the inertia.

Separation of sites according to soil morphology by multivariate PCA was significant ($p<0.001$). Tea2, 12 was separated from other sites with more biogenic aggregates; Tea1, 1 and Tea2, 14 had more amount of physical aggregates.

Factor 1clearly separated sites according to biogenic and physical aggregates, and soil texture; factor 2 separated sites according to total C, respiration, microbial biomass C, small and medium size aggregates. Physical aggregates were correlated with clay content, it shows clay content has influence on physical aggregates formation (Figure Ⅱ.27).

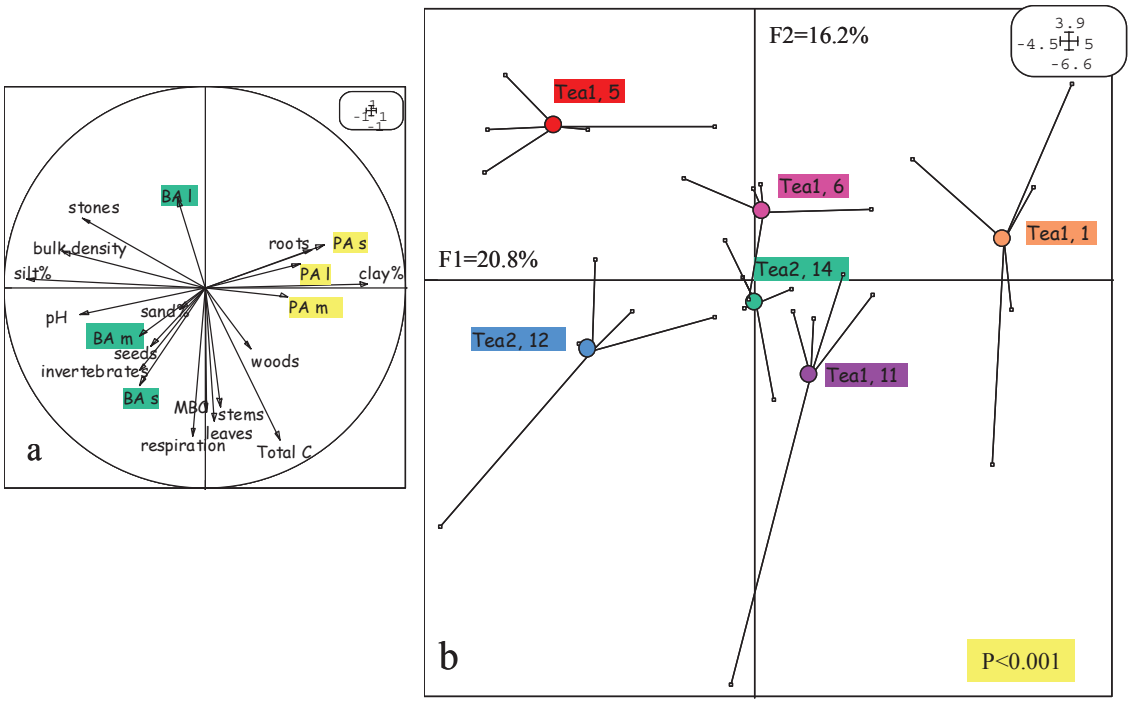


Figure II.27: Ordination of sites by PCA analysis of 13 soil morphology components and all the soil basic properties had analysed.
(a) Correlation circle of variables with factors 1 and 2 of PCA analysis with the 13 soil morphology components and all the soil basic properties had analysed.
(b) Projection of sites in the plane defined by factors 1 and 2. Circles indicate barycentres related by arrows to sites with a common type of land use. p is probability for groups not to be different (permutation test with 10000 repetitions).
P: probability for separation among groups was significant. Factors 1 and 2 explain together 37.0% of the inertia.

Sites Tea1, 11 and Tea2, 12 had higher projection on factor 2, which was determined mainly by soil carbon and biogenic aggregates. Tea2, 12 in Shangmingxuan tea garden had more biogenic aggregates than sites in tea institute (Tea1). Tea1, 11 it had highest total C (31.59 g kg^{-1}) and respiration (0.0301 mol CO_2 kg^{-1}), microbial biomass C was high (311.17 mg kg^{-1}). Tea1, 1 and Tea2, 14 had more physical aggregates than other sites.

Ⅱ.5 Soil aggregate stability distribution analysis by wet-sieving after morphological separation

Ⅱ.5.1 Method and material

Aggregates separated by the visual assessment technique were further analysed by the wet sieving technique. The objective was to intercalibrate the two methods and possibly test the hypothesis that the visual method would be a suitable surrogate for the physical technique that is much more time consuming.

Wet-sieving method (Ⅱ.3.3) was applied to separate water-stable aggregates with diameter 2 mm, 1 mm, 0.5 mm, 0.25 mm and 0.053 mm meshes (Figure Ⅱ.28).

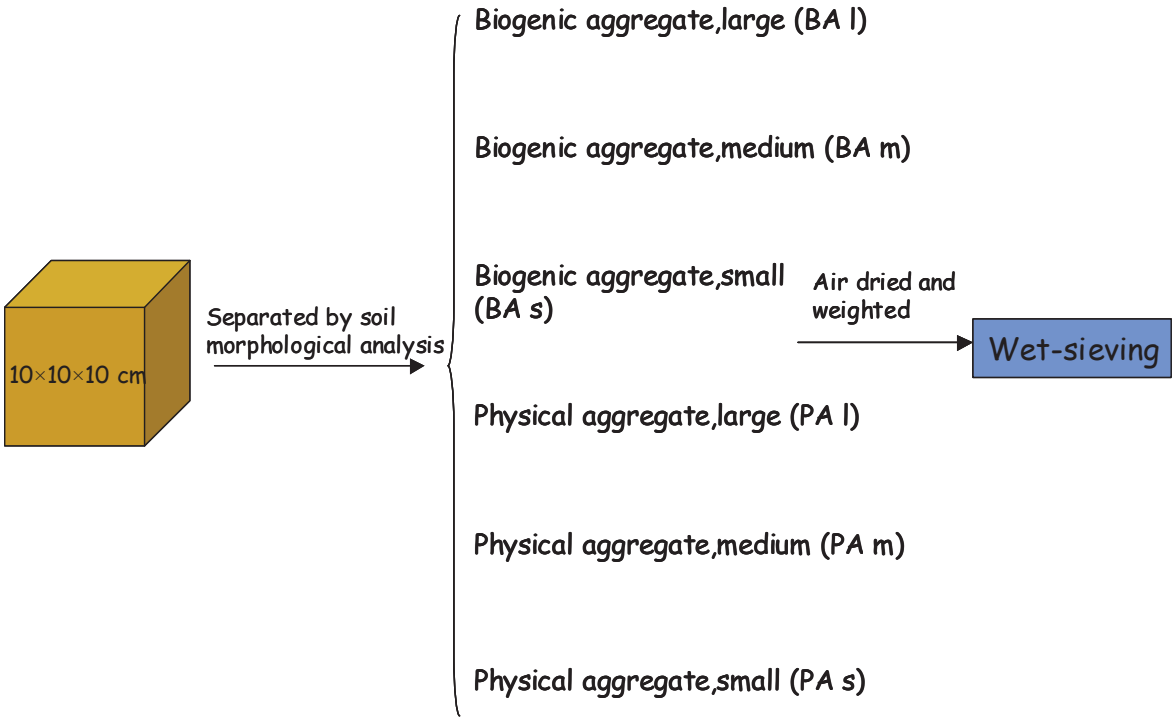
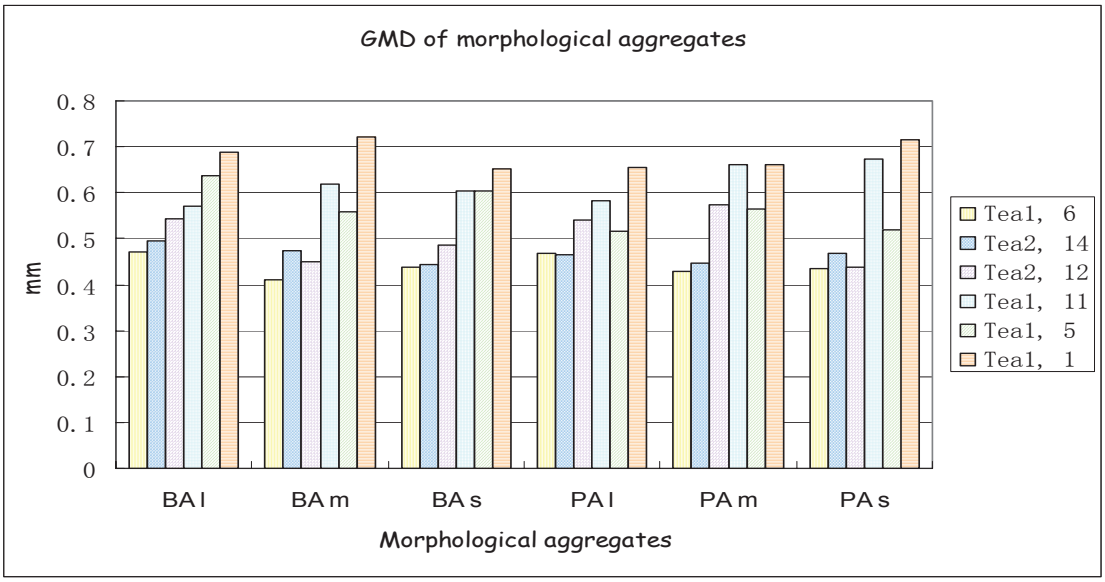


Figure Ⅱ.28: Experimental procedure used to assess water-stable aggregates distribution after soil morphology analysis.

Ⅱ.5.2 Results and discussion

Different morphological aggregates were analysed by wet-sieving and aggregates distribution were gotten (Annexe, Table 15).

GMD was calculated for soil samples belonging to different morphological aggregates (Annexe, Table 16; Figure Ⅱ.29).



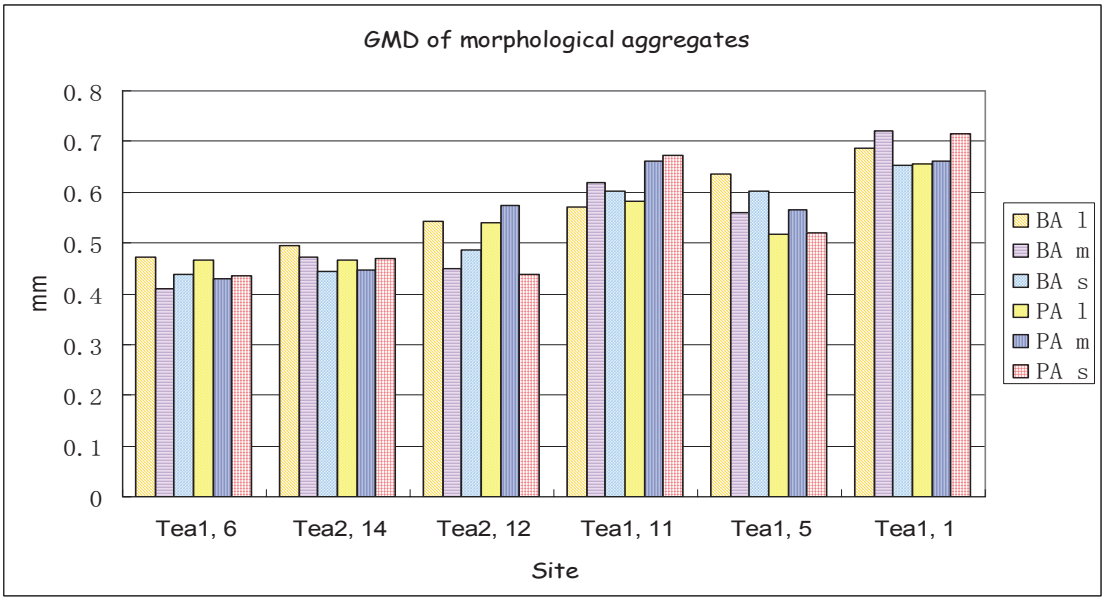


Figure Ⅱ.29: GMD of different morphological aggregates in the 6 sites.

Tea1, 6 and Tea2, 14 had lower GMD for all the six morphological aggregates; Tea1, 1 and Tea1, 11 had higher GMD compared with other sites.

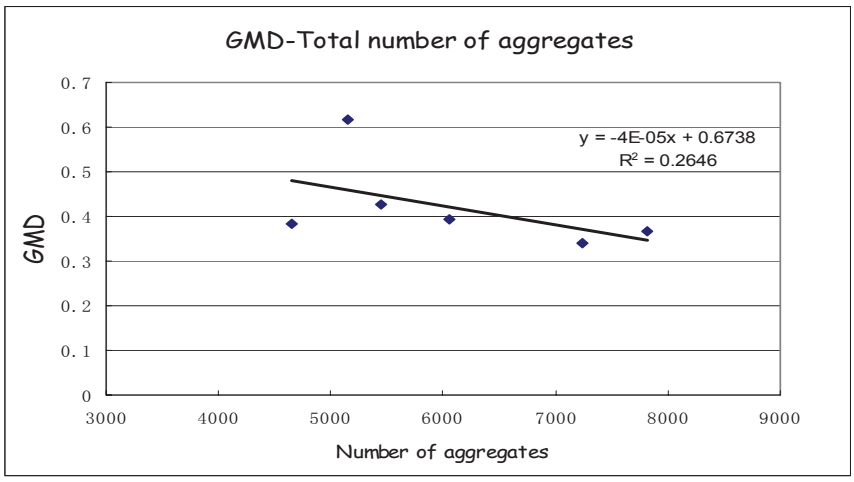


Figure II.30: GMD and total quantity of aggregates in the 6 sites

Coinertia analysis was carried out, aggregates stability distribution measured by GMD was found to be independent on biogenic or physical classification measured by morphological analysis.

Ⅱ.6 Discussion et conclusion

La structure du sol se définit à partir de la distribution spatiale et de l'hétérogénéité des particules organiques et minérales, des agrégats et des pores (Kay and Angers, 1999). La caractérisation de l'aggrégation, de la porosité et de la matière organique est essentielle pour les études du fonctionnement du sol. La formation et la stabilisation des agrégats sont des processus importants à considèrer pour comprendre la genèse et la dynamique de la structure du sol.

1. Formation d'agrégats

L'analyse des blocs intacts de sol par de la méthode visuelle de morphologie du sol (Velasquez, 2004; Velasquez *et al*, 2007) permet d'identifier l'origine des agrégats et leur lien avec la communauté des macro-invertébrés et le mode de gestion du sol. Les agrégats biogéniques sont produits par les activités des macro-invertébrés. Dans les sités étudiés, ces sont principalement des turricules de vers de terre et les constructions des quelques termites endogés. L'analyse multivariée des données collectées dans les 6 sites sélectionés montre une étroite corrélation entre l'abondance des structures biogéniques et les invertébrés est démontrée par la projection sur un plan factoriel des toutes les structures ayant des morphologies distinctes.

L'abondance des agrégats biogéniques est apparue principalement liée à la matière organique du sol tandis que les agrégats physiques étaient plus liés à la teneur en argile (Figure Ⅱ.27). Velasquez *et al.* (2007) ont montré que les agrégats séparés par la méthode de morphologie du sol ont des spectres NIRS distincts, suggérant des origines différentes. Dans la même études, ils ont montré également que dans des sol Amazoniens, une liaison était établie entre le changement de la communautés des macro invertébrés et celui des macro-agrégats, ainsi qu'entre la morphologie du sol et la matière organique du sol et d'autres caractéristiques chimiques du sol.

Il existe des différences significatives de la distribution des agrégats entre les six parcelles étudiées (Figure Ⅱ.26, $p<0.001$). Dans les parcelles Thé 1, 5 de l'Institut du Thé à yingde, replantées il y a à peine 2 ans, les sols montrent des signes de perturbation et les agrégats ont été détruits par le labourage et le nivelage du sol. Dans les parcelles, on a observé la plus faible quantité d'agrégats biogéniques et physiques, tandis que la présence de nombreuses pierres atteste de l'érosion intervenue dans les années antérieures . Dans les parcelles Thé 2, 12 et 14 de la plantation de Shangmingxuan plantées depuis 30 ans, peu soumises au labour et ayant reçu plus d'apport des fumiers et de résidus organiques, les agrégats biogéniques sont en plus grande quantité (Figure Ⅱ.25).

Ces résultats ont montré clairement le grand impact des invertébrés ingénieurs sur la formation des agrégats de grandes tailles. Notre résultats confirment aussi les effets des modes de gestion rapportés dans la littérature. Le labour modifie la structure du sol et distribue de la matière organique riche en énergie dans les couches du sol. Ainsi le type et l'intensité du labour influencent beaucoup les propriétés et les processus du sol et par conséquent, modifient la structure du sol.

La structure du sol est positivement corrélée aux pratiques conservatrices telles que l'apport de matière organique ou le labour minimum (Carter and Stewart, 1996). Golchin *et al.* (1994) formulent l'hypothèse que lorsque la matière végétale (débris foliaires et racines) est incorporée au sol, par le labour ou dans les structures biogéniques crées par la macrofaune, elle stimule la stabilisation des agrégats par la production de matériaux de cimentation d'origine microbienne. L'apport des résidus sous forme de mulche augmente le carbone du sol, modifie la température et l'humidité du sol, affectant à leur tour la faune du sol.

2 Stabilisation des aggrégats

L'étude de la stabilité des agrégats par la méthode classique de tamisage à l'eau sépare ceux qui ont résisté au tamisage dans l'eau mais ne donne pas d'indication sur leur origine. Cette méthode permet cependant d'évaluer les petits agrégats produits

par les foumis et les termites et d'autres processus non pris en compte par la méthode de morphologie.

La moyenne géométrique du diamètre des agrégats (GMD) est calculée à partir des quantités d'agrégats de différentes tailles récupérées après le tamisage sous l'eau Ce paramètre qui résume la stabilité des agrégats est apparu lié à la teneur en argile et en matière organique pour la couche 0-10 cm du sol (Figure Ⅱ.17) ; dans la couche 10-20 cm, elle est plus liée à la matière organique et à la biomasse microbienne (Figure Ⅱ.20).

Il est ainsi confirmé que la stabilisation des agrégats est conditionnée par la teneur en carbone du sol, les microorganismes et l'argile. Les principales matières organiques participant à la stabilisation des agrégats proviennent de la décomposition des résidus végétaux, animaux et microbiens, des substance (gels et polysacharides) synthétisées au cours de la décomposion, et des microorganisme (Lynch and Bragg, 1985; Martens and Frankenberger, 1992; Schlecht-Pietsch *et al*., 1994; Lal, 2000).

La texture du sol a aussi d'influence significative sur la stabilisation des aggrégats.. Dans les sols dont la texture est grossière, le SOC a une plus grande importance pour la stucture du sol; mais dans les sols à texture fine, l'argile joue un rôle croissant avec augmentation de la teneur en argile, en pus, le type d'argile est plus important que la quantité pour l'aggrégation du sol (Kay, 1998). Les particules argileuses affectent l'aggrégation du sol par dilatation et dispersion. Denef and Six (2004) ont trouvé que l'aggrégation et la biomasse microbienne sont étroitement corrélées dans un Mollisol mais elles sont indépendante dans un Oxisol.

Morel *et al*. (1991) ont constaté que la formation instantanée d'agrégats lors qu'ils mettent dans le sol de l'extrait de racines de maïs n'est pas due à l'activité microbienne, ce qui prouve que le mucilage excreté par les racines a un effet adhésif direct sur les particules du sol. Les particules enserrées dans les chevelus racinaires finissent par former des aggrégats qui se stabilisent progressivement (Tisdall and Oades, 1982), Dans notre étude, le groupe d'agrégats dus à l'action des racines n'a pas été défini, mais dans une étude ultérieure, Velasquez *et al*. (2007) l'ont inclus dans les groupes d'agrégats et constaté que ces agrégats recouvraient, pour la plupart,

la catégorie dite ‘physique’.

L’analyse des agrégats stables à l’eau par la méthode classique de tamisage montre de différences significatives entre les 6 sités étudiés. Le diamètre moyen (GMD) des agrégats dans les sites de l’Institut de thé (Thé 1.1 et thé 1.11) est plus grand que dans les 4 autres sites avec une plus grande proporttion d’aggrégats stables. Les sols de ces sites sont argileux et acides, en particulier dans le site thé 1.1 dont la teneur en argile est la plus grande des 6 sites, atteignant 55.1% et 57.3% respectivement dans les horizons 0-10 cm et 10- 20 cm. Dans le site Thé 1.11 où l’apport de résidus est plus important que dans les 3 autres sites du thé, le GMD des agrégats est aussi élevé dans les2 horizons.

La fertilisation chimique en surface est appliquée plus fréquemment dans les sols de la parcelle Thé 1.1 que dans d’autres parcelle, ce qui peut avoir l’effet d’augmenter la densité racinaire dans la couche supérieure du sol (Drew and Saker, 1975), et par conséquent la quantité d’aggrégats ‘racinaires’ et la GMD.

Les différentes catégories d’agrégats séparées par la méthode de morphologie ne présentent pas, contrairement à ce qu’on l’a attendait, de différences en terme de stabilité. Ceci est probablement du au fait que les agents adhésifs sont probablement les mêmes dans les agrégats biogéniques et physiques. La stabilité dans l’eau des agrégats dépend aussi de leur age. Les turricules et excretions fraîchement produits sont très instables mais leur stabilité augmente après au moins un cycle de séchage et réhumidification (Shipitalo and Protz, 1988; Schrader and Haiquan, 1997). Le prétraitement plus souvent utilisé pour le procédé de fractionnement, une immersion brutale dans l’eau, peut avoir détruit les agrégats biogéniques récents. En plus, il y a la possibilité que les agrégats biogéniques aient perdu leur forme originale au cours du vieillissement et ne puissent plus être séparés des agrégats physiques par la méthode visuelle.

Notre étude sur les facteurs de formation et stabilisation des agrégats par les méthodes de morphologie et de tamisage à eau a montré que les microorganismes, la teneur en matière organique du sol et en argile sont corrélés et affectent tous la

stabilisation des aggrégats. Les matières organiques du sol stimulent la formation des agrégats par les invertébrés ingénieurs, et participent ensuite à la stabilisation des agrégats en jouent un double rôle d'agents adhésifs (colloïdes organiques) et de suqelette de la macrostructure, à l'instar des barres de fer dans une structure de béton. Notre étude a fourni des jeux de données qui illustrent bien les processus complexes qui régissent la formation, la stabilisation et le viellissement des agrégats.

Ⅱ.6 Discussion and conclusion

Soil structure assessments are focussed on the spatial arrangement or heterogeneity of soil particles, aggregates, voids and pores (Kay and Angers, 1999). Information on aggregation, organic matter status and porosity are essential elements in the study of soil functions. Aggregate formation and stabilization is probably the major process to study when searching for a comprehensive description of soil structure.

1. Aggregate formation

The analysis of undisturbed soil blocks by the visual method of soil morphology (Velasquez, 2004; Velasquez *et al*, 2007) gives information on the origin of aggregates, and their link to soil macro-invertebrate communities and soil management options. Biogenic aggregates are structures produced by macro-invertebrates. At our study sites, they mostly comprised earthworm casts and a few termite endogeic constructions. The projection of morphological items on a common factorial plan showed that invertebrates had obvious correlation with biogenic aggregates (Figure Ⅱ.26). Biogenic aggregates are related to soil organic matter and physical aggregates are more related to soil clay content (Figure Ⅱ.27). Velasquez *et al* (2007) showed that aggregates separated by this method of soil morphology had significantly different NIRS spectral signatures supporting the expected differences in their origins. This study also showed that changes in macrofaunal communities were significantly correlated to changes of soil macro-aggregation in Amazonian soils. This research also showed significant links between soil morphology and soil chemistry, organic matter and soil macrofauna.

The pattern of soil aggregation determined by visual separation was significantly different in our six studied plots (Figure Ⅱ.26, $p<0.001$). Tea1, 5 in Tea Institute had been replanted 2 years ago. Soil already showed significant signs of perturbation as, aggregates had been destroyed by tillage and leveled off. The smallest numbers of both biogenic and physical aggregates were obtained at this site, and high occurrence

of stones. Tea2, 12 and Tea2, 14 in Shangmingxuan tea garden (Tea2) were tea plantations about 30 yr-old with little mechanical work, more manure and residues input than sites in Tea Institute; a large amount of biogenic aggregates was found in these sites (Figure Ⅱ.25).

These results clearly show the great impact of soil invertebrate engineers in the formation of large aggregates. Our results also confirm effects of management practices as indicated in literature; Tillage modifies soil structure and distributes energy-rich organic substances into the soil profile. Thus, the type and degree of tillage can have a major influence on soil properties and processes and thereby modify soil structure. The latter is positively related to crop and soil management practices such as organic matter inputs, soil nutrient management and conservation tillage practices (Carter and Stewart, 1996).

Golchin *et al.* (1994) proposed that when fresh plant material (as surface residues or roots) enters into the soil, it induces the formation of aggregates because it stimulates the production of microbial-derived binding agents by being a C source for microbial activity. Mulches increase the amount of SOC pool (Duiker and Lal, 1999; Sharma and Acharya, 2000; Jacinthe *et al.*, 2002b), modify temperature and moisture regimes and impact soil fauna.

2. Aggregate stabilisation

Aggregate stability studied by the classical method of wet-sieving focus on aggregates that survive shaking in water not paying any attention to their origin. This method also allows to assess small aggregates (> 53μm) made by ants, termites and other processes not considered in the morphological assessment.

Soil mean geometric diameters were clearly related to clay content and organic matter for soils taken from 0-10 cm (Figure Ⅱ.17) and more related to soil organic matter and microorganisms for soils taken from 10-20 cm (Figure Ⅱ.20).

This confirms that aggregate stabilisation is mediated by soil organic carbon (SOC), microbiota, ionic bridging, clay and carbonates. The main organic materials for aggregate stabilization are: (i) decomposition products of plant, animal, and

microbial remains; (ii) the microorganisms themselves; and (iii) the products of microbial synthesis (e.g. polysaccharides and gums) formed during decomposition of organic residues (Lynch and Bragg, 1985; Martens and Frankenberger, 1992; Schlecht-Pietsch *et al.*, 1994; Lal, 2000). When organic residues were added, they fed more microorganisms and macrofauna, which produced more aggregates and relased products of aggregate stabilization.

Soil texture has a significant influence on aggregate stabilization. In coarse-textured soils, the SOC has a greater influence on structure; while with increasing clay content the type of clay is more important than the amount in determining aggregation (Kay, 1998). Clay concentration physically affects aggregation through swelling and dispersion. Denef and Six (2004) found that in the Mollisol, significant regressions were found between aggregation and microbial biomass, in contrast, aggregation was found to be independent from the microbial biomass content in the Oxisol.

Mucilages produced by roots may stick soil particles directly together. As Morel *et al*. (1991) found that adding extracted maize root mucilage to soils led to an instantaneous aggregate formation, without any interference of microbial activity, it proved that mucilages produced by roots may stick soil particles directly together. The entanglement of particles by roots may be another mechanism that forms and stabilizes macroaggregates (Tisdall and Oades, 1982). In our study, root aggregates have not been separated as a specific group. This improvement of the technique has been proposed after our work and included in the Velasquez *et al*. (2007) technical paper. Many of them may have fallen into the “physical” category.

The assessment of water-stable aggregate by conventional method of wet-sieving showed that differences of GMD among the six studied sites (samples taken from 0-10 cm and 10-20 cm) were significant. Aggregate GMDs in sites Tea1, 1 and Tea1, 11 (Tea Institute) were higher than in the other 4 sites (Figure Ⅱ.21) with a higher proportion of water-stable macro-aggregates. Soils in our study were clayey and acidic, especially the sites in the Tea Institute: Tea1, 1 had the highest clay content for

soils taken from 0-10 cm (55.1%) and 10-20 cm (57.3) among the 6 sites. More organic residues had been applied in Tea 1, 11 than at the other 3 sites in Tea1, and GMD was greater in both layers.

Chemical fertilizers had been applied on the surface of soil in Tea1, 1, with a higher frequency than at other sites in Tea Institute. This may have enhanced root density at the surface layer (0-10 cm) (Drew and Saker, 1975), and then have increases the amount of root macroaggregates and increased the GMD parameter.

Contrary to our expectations, aggregates separated by morphological analysis did not have different stabilities according to their origin. This is probably because agents of aggregate stabilization (e.g. colloids, microorganisms) are the same in biogenic and physical aggregates. Water stability of the aggregates is known to depend on their ages. Fresh cast and excretion generally are highly unstable; they will stabilize after at least one drying/rewetting cycle (Shipitalo and Protz, 1988; Schrader and Haiquan, 1997). Moreover, there is the possibility already mentioned that biogenic aggregates, which existed long time, were classified into physical aggregates because the typical shape created by organism could not be identified by visual separation.

The most common fractionation procedure for pre-treatment before wet-sieving is a rapid immersion of air-dried samples in water, which simulates slaking under a severe wetting stress (Denef *et al.*, 2001). There are two pre-treatments before wet sieving: air drying followed by rapid immersion in water (slaked) and air drying plus capillary rewetting to field capacity plus 5% (capillary-wetted) (Six *et al*., 1998). In our study slaking was chosen as pre-treatment. When air-dry soil is directly submerged in water; the air that is trapped inside the soil pores is rapidly displaced with water. Weak aggregates are disrupted as a consequence of the sudden release of this large buildup of internal air pressure (Cambardella and Elliott, 1993; Gale *et al*., 2000). Newly formed biogenic aggregates may have been destroyed by slaking (Blanchart *et al*., 1993).

Our study on soil structure by morphological analysis and wet-seving was

focussed on the factors of formation and stabilization of soil aggregates. Our analyses clearly showed the link among microorganisms, soil organic matter and clay content with soil aggregates stabilization is affected. Soil organic matter plays a double role as it enhances the production of aggregates by ecosystem engineers (invertebrates, fungi and roots) and further participates in the stabilization of the newly formed aggregates. Again, organic matter may have two clearly separate functions in the stabilization, that of a glue (colloidal organic matter) that sticks particles together, or that of a timber (particulate organic matter) that frames the whole macrostructure. Our work provides the diverse sets of data to illustrate this complex process and emphasize the role of the different actors involved.

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Annexe

Table 1: Physical properties: 6 variables (mean values of 5 points). Absolute highest and minimum values are marked with green and yellow colour respectively.

Site N°	Plantation	Depth cm	Bulk density g cm^{-3}	Water content %	Soil strength kg cm^{-3}	Sand %	Silt %	Clay %
1	Tea1, 1	0-10	1.09	24.9	15.32	8.8	32.5	58.7
		10-20			27.90	11.7	25.9	62.4
2	Tea1, 2	0-10	0.98	17.5	1.76	15.6	32.6	51.8
		10-20			11.77	17.1	29.3	53.6
3	Tea1, 3	0-10	1.23	21.7	7.51	16.6	35.3	48.1
		10-20			8.72	12.9	32.3	54.9
4	Tea1, 4	0-10	1.45	15.6	9.83	27.6	41.6	30.8
		10-20			30.58	23.9	40.0	36.1
5	Tea1, 5	0-10	1.21	15.1	2.97	24.6	40.9	34.5
		10-20			10.73	22.7	41.3	36.0
6	Tea1, 6	0-10	1.12	23.2	5.57	25.1	38.3	36.7
		10-20			16.31	23.2	36.2	40.6
7	Tea1, 7	0-10	1.21	22.1	8.44	16.9	28.7	54.3
		10-20			14.01	14.5	28.7	56.8
8	Tea1, 8	0-10	1.26	22.1	6.62	14.0	26.7	59.3
		10-20			12.08	13.3	28.4	58.3
9	Tea1, 9	0-10	1.31	20.6	11.54	19.9	33.2	46.9
		10-20			27.89	18.0	31.0	51.0
10	Tea1, 10	0-10	1.13	24.0	11.40	17.8	36.5	45.7
		10-20			15.09	14.5	37.8	47.7

Site N°	Plantation	Depth cm	Bulk density g cm^{-3}	Water content %	Soil strength kg cm^{-3}	Sand %	Silt %	Clay %
11	Tea1, 11	0-10	1.19	23.4	9.31	17.4	34.3	48.3
		10-20			9.51	13.1	37.2	49.7
12	Tea2, 12	0-10	1.15	23.1	26.27	19.6	42.5	37.9
		10-20			27.60	18.9	42.5	38.5
14	Tea2, 14	0-10	1.21	23.0	17.70	19.4	31.2	49.4
		10-20			24.95	15.6	35.8	48.6
15	Tea2, 15	0-10	1.16	21.7	16.42	20.1	41.9	38.0
		10-20			13.94	17.8	36.0	46.2
16	Sugarcane	0-10	1.25	18.6	9.00	29.0	47.9	23.1
		10-20			23.44	32.1	49.7	18.2
17	Orange	0-10	1.29	15.7	8.36	22.9	58.5	18.6
		10-20			24.60	23.6	52.8	23.6
18	Pine	0-10	1.22	23.0	8.28	12.0	53.1	34.9
		10-20			9.73	10.1	49.2	40.7
19	Bamboo	0-10	0.97	34.1	6.71	23.3	36.9	39.8
		10-20			14.93	25.4	42.5	32.2
20	Wasteland	0-10	1.49	15.1	20.45	22.9	43.1	34.0
		10-20			18.90	20.8	43.4	35.8

Table 2: Reduced physical parameter values and sub-indicator.

Plantation	Bulk density	Water content	Sand	Silt	Clay	Sub-indicator	Reduced sub-indicator value
Tea1, 8	0.49	0.43	0.33	0.1	1	611.07	0.10
Tea1, 1	0.8	0.57	0.1	0.26	0.99	365.92	0.19
Tea1, 7	0.58	0.43	0.46	0.16	0.89	201.91	0.25
Tea2, 14	0.58	0.48	0.57	0.23	0.78	-25.45	0.34
Tea1, 9	0.42	0.36	0.6	0.28	0.73	-55.78	0.35
Tea1, 3	0.56	0.41	0.45	0.34	0.75	-94.2	0.36
Tea1, 11	0.62	0.49	0.48	0.32	0.76	-87.98	0.36
Tea1, 10	0.73	0.52	0.5	0.38	0.7	-357.13	0.46
Bamboo	1	1	0.74	0.39	0.57	-570.1	0.54
Wasteland	0.1	0.1	0.73	0.56	0.44	-580.4	0.55
Pine	0.57	0.47	0.24	0.85	0.46	-635.92	0.57
Tea1, 2	0.98	0.22	0.4	0.27	0.83	-726.37	0.60
Tea2, 12	0.69	0.48	0.58	0.55	0.53	-753.7	0.61
Tea2, 15	0.68	0.41	0.6	0.53	0.53	-815.69	0.63
Tea1, 4	0.17	0.13	0.94	0.52	0.37	-866.34	0.65
Tea1, 6	0.73	0.48	0.82	0.43	0.5	-947.29	0.68
Tea2, 13	0.59	0.36	0.86	0.5	0.42	-1062.11	0.72
Tea1, 5	0.59	0.1	0.8	0.5	0.45	-1273.73	0.80
Sugarcane	0.51	0.26	1	0.7	0.2	-1605.1	0.93
Orange	0.44	0.13	0.73	1	0.1	-1798.59	1.00
Factor 1	-1452	1533	-1874	-2147	2885	a = 611.07	
Factor 2	-3853	2011	488	1214	-1255	b = -1798.59	

Table 3: Chemical properties: 4 variables (mean values of 5 points). Absolute highest and minimum values for each depth are marked with green and yellow colour.

		0–10cm				10–20cm			
Site N°	Plantation	K^+ mg kg^{-1}	Ca^{2+} mg kg^{-1}	Mg^{2+} mg kg^{-1}	pH	K^+ mg kg^{-1}	$Ca2^+$ mg kg^{-1}	Mg^{2+} mg kg^{-1}	pH
1	Tea1, 1	19.4	290.4	21.7	4.11	5.8	586	28.1	4.31
2	Tea1, 2	6.1	164	11.4	3.90	6.2	183	18.3	3.98
3	Tea1, 3	33.6	366.1	29.5	4.51	21.7	654.2	45.1	4.93
4	Tea1, 4	11.4	596.4	38.7	5.75	4.5	869	36.6	5.95
5	Tea1, 5	25.4	673.1	25.5	5.57	4.4	710.5	33.9	5.61
6	Tea1, 6	4.8	375.8	27.1	3.74	2.9	328.9	15.5	3.98
7	Tea1, 7	34.9	594.8	71.3	5.24	65.5	863.8	88.2	5.48
8	Tea1, 8	33	394.7	34.9	4.26	20.8	373.4	22.4	4.31
9	Tea1, 9	11	423.4	27	5.16	7.8	785.1	35.4	5.54
10	Tea1, 10	18.7	401.7	36.8	3.91	11.1	232.9	24.7	3.89
11	Tea1, 11	45.5	456.4	34.1	3.96	69.1	794.1	44	4.41
12	Tea2, 12	4.8	556.9	25.1	4.61	4.4	380.3	17.6	4.55
13	Tea2, 13	7.5	881.4	43.3	4.96	1.7	547.1	17	4.78
14	Tea2, 14	10.2	689	32.3	4.92	3.1	398	21	4.72
15	Tea2, 15	9.1	881.9	42.5	5.00	3.2	495.1	28.6	4.70
16	Sugarcane	5.2	925.1	23.8	5.97	5.4	2060.9	25.5	7.48
17	Orange	228.6	2181.7	50.6	7.97	186.4	2334.4	68.5	8. 29
18	Pine	4.3	513	28.1	5.25	2.1	590.8	27.3	5.56
19	Bamboo	8.2	917.9	40.4	5.54	5.8	789.3	34.5	5.37
20	Wasteland	3.8	863.5	39.1	6.17	1.6	734.2	16.8	6.24

Table 4: Reduced chemical parameter values and sub-indicator.

Plantation	K^+	Ca^{2+}	Mg^{2+}	pH	Sub-indicator	Reduced sub-indicator
Tea1, 2	0.11	0.10	0.10	0.14	910.13	0.10
Tea1, 1	0.16	0.16	0.25	0.18	1592.17	0.19
Tea1, 6	0.10	0.19	0.34	0.10	1631.24	0.20
Tea2, 12	0.10	0.28	0.31	0.29	2092.08	0.26
Tea1, 10	0.16	0.21	0.48	0.14	2181.99	0.27
Tea1, 3	0.22	0.19	0.37	0.26	2215.22	0.28
Tea1, 9	0.13	0.22	0.33	0.40	2293.34	0.29
Tea1, 11	0.27	0.23	0.44	0.15	2331.69	0.29
Tea1, 8	0.22	0.20	0.45	0.21	2341.66	0.30
Pine	0.10	0.26	0.35	0.42	2417.48	0.31
Tea2, 14	0.13	0.33	0.41	0.35	2656.00	0.34
Tea1, 5	0.19	0.33	0.31	0.49	2748.20	0.35
Sugarcane	0.11	0.44	0.29	0.57	2964.35	0.38
Tea1, 4	0.13	0.29	0.51	0.53	3149.12	0.41
Tea2, 13	0.11	0.42	0.58	0.36	3254.99	0.42
Tea2, 15	0.12	0.42	0.57	0.37	3254.74	0.42
Bamboo	0.12	0.44	0.54	0.48	3422.65	0.44
Wasteland	0.10	0.41	0.52	0.62	3548.66	0.46
Tea1, 7	0.22	0.29	1.00	0.42	4313.25	0.57
Orange	1.00	1.00	0.69	1.00	7491.32	1.00
Factor 1	2506	3256	1406	2830	a = 7491.32	
Factor 2	-706	-346	8504	-402	b = 910.13	

Table 5: SOM properties: 6 variables (mean values of 5 points). Absolute highest and minimum values are marked with green and yellow colour.

Site N°	Plantation	Depth cm	MBC mg kg^{-1}	MBC/TC %	Total C ‰	Total N ‰	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}
1	Tea1, 1	0-10	197.9	0.81	23.20	1.89	101.3	211.4
		10-20	150.8	1.34	13.63	1. 04	80.0	112.9
2	Tea1, 2	0-10	118.6	0.53	24.41	2.10	99.0	150.0
		10-20	185.3	1.01	18.32	1.61	78.4	145.6
3	Tea1, 3	0-10	205.2	1.37	15.05	1.35	87.8	271.5
		10-20	205.8	1.50	13.65	1.23	48.5	124.1
4	Tea1, 4	0-10	172.5	2.06	9.37	0.69	59.4	54.1
		10-20	221.8	2.68	9.23	0.74	50.8	39.6
5	Tea1, 5	0-10	80.4	0.57	13.69	1.25	70.2	61.0
		10-20	160.1	1.20	13.29	1.28	53.6	72.9
6	Tea1, 6	0-10	261.0	0.82	33.23	2.85	89.9	261.8
		10-20	176.4	0.99	18.06	1.61	60.4	93.7
7	Tea1, 7	0-10	198.6	2.04	10.35	0.75	77.4	188.3
		10-20	215.4	2.76	7.92	0.52	69.5	135.3
8	Tea1, 8	0-10	179.4	1.65	11.09	0.88	88.2	268.7
		10-20	223.2	2.41	10.28	0.79	68.0	270.4
9	Tea1, 9	0-10	193.5	1.20	16.16	1.30	70.5	239.6
		10-20	208.6	1.52	14.62	1.15	48.6	101.2
10	Tea1, 10	0-10	181.2	0.69	26.63	2.31	71.0	204.6
		10-20	193.2	0.92	21.21	1.86	95.0	93.8
11	Tea1, 11	0-10	144.7	0.50	28.95	2.56	37.4	199.4
		10-20	169.6	0.70	24.15	2.07	33.5	140.5
12	Tea2, 12	0-10	512.0	2.20	23.85	2.41	81.4	184.1

		10-20	233.1	1.25	19.23	2.04	62.5	107.6
13	Tea2, 13	0-10	379.7	1.43	25.42	2.38	72.3	190.9
		0-20	190.4	1.05	18.13	1.80	83.8	82.0
Site N°	Plantation	Depth cm	MBC mg kg^{-1}	MBC/TC %	Total C ‰	Total N ‰	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}
14	Tea2, 14	0-10	473.8	1.91	23.60	2.37	59.8	176.4
		10-20	196.7	1.29	16.41	1.86	62.6	70.6
15	Tea2, 15	0-10	372.6	1.67	22.50	2.10	55.8	137.1
		10-20	146.6	0.85	17.19	1.70	52.9	84.6
16	Sugarcane	0-10	262.1	1.61	16.04	1.28	49.9	63.5
		10-20	216.9	2.00	10.75	0.88	28.7	49.0
17	Orange	0-10	242.5	1.16	21.51	1.49	48.3	104.6
		10-20	190.6	0.97	19.60	1.33	28.3	67.8
18	Pine	0-10	179.6	1.20	14.54	1.58	76.4	92.6
		10-20	133.0	1.12	9.88	1.16	61.8	46.5
19	Bamboo	0-10	388.7	2.48	16.68	1.98	83.6	78.1
		10-20	181.4	1.89	8.88	1.32	47.8	37.1
20	Wasteland	0-10	159.6	1.54	11.82	1.07	57.1	43.9
		10-20	145.5	1.45	10.62	1.06	43.0	25.9

Table 6: Reduced SOM parameters and sub-indicator.

Plantation	MBC	MBC/TC	C ‰	N ‰	Sub-indicator	Reduced sub-indicator
Tea1, 5	0.10	0.13	0.26	0.33	1176.32	0.10
Tea1, 4	0.29	0.81	0.10	0.10	1472.55	0.18
Tea1, 8	0.31	0.62	0.16	0.18	1547.51	0.20
Wasteland	0.27	0.57	0.19	0.26	1601.12	0.21
Tea1, 7	0.35	0.80	0.14	0.12	1640.61	0.22
Tea1, 9	0.34	0.42	0.36	0.35	1974.19	0.31
Pine	0.31	0.42	0.29	0.47	2011.20	0.32
Tea1, 3	0.36	0.50	0.31	0.37	2049.26	0.33
Sugarcane	0.48	0.61	0.35	0.35	2351.00	0.41
Tea1, 2	0.18	0.11	0.67	0.68	2436.19	0.43
Orange	0.44	0.40	0.56	0.43	2552.90	0.46
Tea1, 1	0.34	0.24	0.62	0.60	2615.80	0.48
Tea1, 10	0.31	0.19	0.75	0.77	2972.18	0.57
Tea1, 11	0.23	0.10	0.84	0.88	3066.78	0.60
Bamboo	0.74	1.00	0.38	0.63	3592.29	0.74
Tea2, 15	0.71	0.63	0.60	0.68	3627.97	0.75
Tea2, 13	0.72	0.52	0.71	0.80	3902.98	0.82
Tea1, 6	0.48	0.24	1.00	1.00	4011.63	0.85
Tea2, 14	0.92	0.74	0.64	0.80	4300.70	0.93
Tea2, 12	1.00	0.87	0.65	0.82	4581.31	1.00
Factor 1	470	-709	3635	3466	a = 4581.31	
Factor 2	5029	4125	3	257	b = 1176.32	

Table 7: Soil macrofauna density (ind m^{-2}) at the 20 sites (mean values of 5 points). Absolute highest values were marked with green colour.

Site N°	Plantation	Oligo Oligo	For	Der	Col,a	Col,l	Isopod	Chi	Hem	Ort	Lep,l	Spi	Dip	Dip,l	Bla	Gas	Isoptera
1	Tea1, 1	67.2	156.8	51.2	12.8	6.4	9.6	3.2	3.2	16.0	3.2	3.2	0.0	0.0	67.2	3.2	0.0
2	Tea1, 2	0.0	28.8	0.0	0.0	0.0	0.0	0.0	137.6	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0
3	Tea1, 3	89.6	233.6	0.0	0.0	3.2	0.0	0.0	0.0	3.2	0.0	3.2	0.0	6.4	0.0	0.0	0.0
4	Tea1, 4	54.40	22.40	6.4	0.0	60.8	0.0	3.2	0.0	0.0	0.0	6.4	0.0	0.0	0.0	0.0	0.0
5	Tea1, 5	35.2	550.4	16.0	0.0	41.6	0.0	0.0	0.0	6.4	0.0	3.2	0.0	0.0	3.2	6.4	0.0
6	Tea1, 6	41.6	3.2	3.2	19.2	9.6	16.0	0.0	3.2	0.0	0.0	6.4	3.2	0.0	0.0	0.0	0.0
7	Tea1, 7	64.0	12.8	3.2	0.0	3.2	3.2	32.0	3.2	0.0	6.4	0.0	3.2	0.0	9.6	9.6	0.0
8	Tea1, 8	6.4	390.4	0.0	9.6	3.2	0.0	3.2	0.0	0.0	19.2	0.0	16.0	0.0	0.0	3.2	0.0
9	Tea1, 9	6.4	115.2	0.0	0.0	12.8	0.0	0.0	0.0	0.0	12.8	3.2	3.2	3.2	0.0	3.2	0.0
10	Tea1, 10	67.2	16.0	0.0	9.6	9.6	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0
11	Tea1, 11	278.4	188.8	0.0	3.2	0.0	0.0	0.0	3.2	0.0	3.2	12.8	35.2	0.0	0.0	3.2	0.0
12	Tea2, 12	502.4	38.4	0.0	12.8	0.0	19.2	19.2	6.4	0.0	0.0	0.0	9.6	0.0	0.0	3.2	0.0
13	Tea2, 13	150.4	403.2	3.2	28.8	6.4	0.0	19.2	3.2	0.0	0.0	0.0	32.0	0.0	0.0	3.2	0.0
14	Tea2, 14	204.8	195.2	3.2	16.0	3.2	0.0	12.8	3.2	0.0	0.0	0.0	16.0	0.0	0.0	0.0	0.0
15	Tea2, 15	307.2	310.4	3.2	9.6	0.0	12.8	3.2	3.2	0.0	3.2	12.8	3.2	0.0	3.2	0.0	0.0
16	Sugarcane	233.6	694.4	16.0	28.8	3.2	3.2	16.0	6.4	0.0	0.0	19.2	0.0	9.6	6.4	0.0	0.0
17	Orange	323.2	64.0	22.4	16.0	41.6	54.4	124.8	0.0	3.2	0.0	16.0	0.0	0.0	9.6	6.4	3.2
18	Pine	76.8	272.0	3.2	3.2	19.2	3.2	3.2	0.0	0.0	0.0	12.8	3.2	3.2	0.0	0.0	0.0
19	Bamboo	252.8	32.0	0.0	3.2	3.2	112.0	9.6	0.0	0.0	0.0	3.2	44.8	0.0	0.0	0.0	0.0
20	Wasteland	70.4	364.8	0.0	0.0	6.4	0.0	0.0	0.0	0.0	0.0	0.0	3.2	0.0	3.2	6.4	0.0

Table 8: Reduced soil macrofauna density values and sub-indicator.

Plantation	Oligo	Der	Isopoda	Chi	Ort	Dip	Bla	Isoptera	Sub-indicator	Reduced sub-indicator
Tea1, 2	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	184.30	0.10
Tea1, 9	0.11	0.10	0.10	0.10	0.10	0.16	0.10	0.10	195.90	0.11
Tea1, 10	0.22	0.10	0.10	0.10	0.10	0.10	0.10	0.10	227.20	0.13
Tea1, 3	0.26	0.10	0.10	0.10	0.28	0.10	0.10	0.10	234.67	0.14
Wasteland	0.23	0.10	0.10	0.10	0.10	0.16	0.14	0.10	235.99	0.14
Tea1, 8	0.11	0.10	0.10	0.12	0.10	0.42	0.10	0.10	236.87	0.14
Tea1, 4	0.20	0.21	0.10	0.12	0.10	0.10	0.10	0.10	259.22	0.15
Tea1, 6	0.17	0.16	0.23	0.10	0.10	0.16	0.10	0.10	265.05	0.16
Tea1, 5	0.16	0.38	0.10	0.10	0.46	0.10	0.14	0.10	265.58	0.16
Pine	0.24	0.16	0.13	0.12	0.10	0.16	0.10	0.10	272.80	0.16
Tea1, 7	0.21	0.16	0.13	0.33	0.10	0.16	0.23	0.10	360.40	0.23
Tea2, 14	0.47	0.16	0.10	0.19	0.10	0.42	0.10	0.10	410.88	0.27
Tea2, 13	0.37	0.16	0.10	0.24	0.10	0.74	0.10	0.10	435.54	0.28
Tea2, 15	0.65	0.16	0.20	0.12	0.10	0.16	0.14	0.10	438.34	0.29
Tea1, 1	0.22	1.00	0.18	0.12	1.00	0.10	1.00	0.10	441.40	0.29
Tea1, 11	0.60	0.10	0.10	0.10	0.10	0.81	0.10	0.10	444.74	0.29
Sugarcane	0.52	0.38	0.13	0.22	0.10	0.10	0.19	0.10	466.04	0.31
Tea2, 12	1.00	0.10	0.25	0.24	0.10	0.29	0.10	0.10	631.42	0.43
Bamboo	0.55	0.10	1.00	0.17	0.10	1.00	0.10	0.10	707.82	0.48
Orange	0.68	0.49	0.54	1.00	0.28	0.10	0.23	1.00	1417.32	1.00
Factor 1	279	1874	261	1539	1084	-151	1041	1562	a = 1417.32	
Factor 2	1673	-884	1086	742	-1583	855	-1415	551	b = 184.30	

Table 9: 11 Separation of soil among morphological items at the 20 sampled sites (relative units obtained by grid counting). Absolute highest values marked with green colour.

Site	Plantation	BA l	BA m	BA s	PA l	PA m	PA s	Roots	Stones	Woods	Stems	Seeds
1	Tea1, 1	13	98	54	0	35	41	29	14	0	0	0
2	Tea1, 2	5	32	39	0	8	56	15	69	0	2	0
3	Tea1, 3	23	65	65	31	21	27	12	87	0	0	0
4	Tea1, 4	12	110	128	10	46	82	45	12	0	0	0
5	Tea1, 5	7	36	107	0	4	40	11	7	0	0	0
6	Tea1, 6	18	217	76	0	14	30	67	11	0	0	0
7	Tea1, 7	0	92	97	0	43	34	8	13	0	2	0
8	Tea1, 8	6	17	23	0	37	90	34	63	0	3	0
9	Tea1, 9	0	98	88	0	21	16	0	18	0	15	0
10	Tea1, 10	0	93	83	0	31	138	135	2	4	3	1
11	Tea1, 11	37	107	108	0	0	22	0	4	4	53	0
12	Tea2, 12	0	125	76	0	28	39	30	46	4	25	10
13	Tea2, 13	13	244	82	0	50	50	37	39	0	0	2
14	Tea2, 14	20	243	58	21	68	27	47	19	0	0	1
15	Tea2, 15	15	175	202	0	0	1	58	5	8	0	0
16	Sugarcane	7	78	132	0	0	24	6	15	0	13	0
17	Orange	20	69	95	18	12	64	0	19	2	0	41
18	Pine	0	256	92	0	0	11	4	0	0	2	0
19	Bamboo	15	105	120	0	4	11	280	164	0	0	1
20	Wasteland	0	104	64	0	9	28	65	188	0	0	0

Table 10: Reduced soil morphological items values and sub-indicator.

Plantation	BA l	BA s	PA l	PA m	Roots	Stones	Woods	Stems	Seeds	Sub -indicator	Reduced sub-indicator
Wasteland	0.10	0.31	1.00	0.88	0.31	1.00	0.10	0.10	0.10	-5.65	0.10
Bamboo	0.46	0.59	1.00	0.95	1.00	0.89	0.10	0.10	0.12	74.87	0.15
Tea1, 3	0.66	0.31	0.10	0.72	0.14	0.52	0.10	0.10	0.10	166.04	0.21
Tea1, 2	0.22	0.18	1.00	0.89	0.15	0.43	0.10	0.13	0.10	268.29	0.28
Tea1, 8	0.25	0.10	1.00	0.51	0.21	0.40	0.10	0.15	0.10	288.57	0.30
Tea2, 14	0.59	0.28	0.39	0.10	0.25	0.19	0.10	0.10	0.12	410.81	0.38
Pine	0.10	0.45	1.00	1.00	0.11	0.10	0.10	0.13	0.10	491.04	0.43
Tea1, 1	0.42	0.26	1.00	0.54	0.19	0.17	0.10	0.10	0.10	508.03	0.44
Tea1, 6	0.54	0.37	1.00	0.81	0.32	0.15	0.10	0.10	0.10	531.22	0.46
Tea1, 7	0.10	0.47	1.00	0.43	0.13	0.16	0.10	0.13	0.10	557.06	0.48
Tea2, 13	0.42	0.40	1.00	0.34	0.22	0.29	0.10	0.10	0.14	561.09	0.48
Tea1, 9	0.10	0.43	1.00	0.72	0.10	0.19	0.10	0.35	0.10	562.45	0.48
Tea1, 5	0.27	0.52	1.00	0.95	0.14	0.13	0.10	0.10	0.10	564.92	0.48
Tea1, 4	0.39	0.63	0.71	0.39	0.24	0.16	0.10	0.10	0.10	597.22	0.50
Tea1, 10	0.10	0.40	1.00	0.59	0.53	0.11	0.55	0.15	0.12	606.12	0.51
Sugarcane	0.27	0.65	1.00	1.00	0.12	0.17	0.10	0.32	0.10	682.59	0.56
Tea2, 12	0.10	0.37	1.00	0.63	0.20	0.32	0.55	0.52	0.32	777.58	0.62
Orange	0.59	0.46	0.48	0.84	0.10	0.19	0.33	0.10	1.00	785.67	0.63
Tea2, 15	0.46	1.00	1.00	1.00	0.29	0.12	1.00	0.10	0.10	1248.47	0.94
Tea1, 11	1.00	0.53	1.00	1.00	0.10	0.12	0.55	1.00	0.10	1341.78	1.00
Factor 1	669	2422	-217	-1414	-35	-486	2155	1406	8	a = 1341.78	
Factor 2	1214	-123	2262	951	-1929	-1755	30	109	1329	b = -5.65	

Table 11: General soil properties (MBC: carbon in microbial biomass).

Sites	MBC	Total C	Respiration	Bulk density	Sand	Silt	Clay	pH
0-10 cm	mg kg^{-1}	g kg^{-1}	mol CO_2 kg^{-1}	g cm^{-3}	%	%	%	
Tea1, 1	290.93	22.98	0.0197	1.03	17.3	27.6	55.1	4.17
Tea1, 5	204.84	13.11	0.0175	1.27	20.0	46.3	33.8	5.12
Tea1, 6	306.83	21.42	0.0188	1.17	26.9	39.8	33.3	4.01
Tea1, 11	311.17	31.59	0.0246	1.11	22.0	34.9	43.1	4.61
Tea2, 12	425.04	19.02	0.0301	1.10	20.7	40.6	38.7	4.19
Tea2, 14	326.53	23.08	0.0250	1.26	22.7	43.5	33.8	4.76
10-20 cm	MBC	Total C	Respiration	Bulk density	Sand	Silt	Clay	pH
Tea1, 1	85.45	14.84	0.0145	1.16	14.0	28.7	57.3	4.19
Tea1, 5	136.21	9.77	0.0177	1.41	20.0	41.3	38.7	5.02
Tea1, 6	230.02	18.19	0.0172	1.26	25.2	35.3	39.5	4.10
Tea1, 11	342.36	27.97	0.0215	1.16	17.4	37.1	45.5	4.35
Tea2, 12	298.96	13.76	0.0158	1.15	18.6	43.3	38.0	4.19
Tea2, 14	264.60	18.06	0.0184	1.28	24.1	41.2	34.7	4.56

Table 12: Weights of different aggregate diameters fractions and values of GMD (Soil samples taken from depth of 0-10 cm, average values of the two sub-samples).

Site	2 mm (g)	1 mm (g)	0.5 mm (g)	0.25 mm (g)	0.053 mm (g)	GMD mm (Geometrical diameter)
Tea1, 1	5.68	3.22	14.55	15.01	9.13	0.519
Tea1, 1	11.98	6.06	12.33	9.44	10.16	0.651
Tea1, 1	7.04	4.16	12.20	13.33	10.92	0.523
Tea1, 1	4.09	5.10	13.84	13.14	6.36	0.566
Tea1, 1	6.06	6.65	14.84	12.80	10.72	0.551
Tea1, 5	3.86	5.14	13.09	12.46	9.52	0.513
Tea1, 5	4.74	4.51	9.65	9.85	14.10	0.450
Tea1, 5	2.75	3.29	9.64	9.72	18.99	0.361
Tea1, 5	9.99	5.48	10.82	7.75	8.97	0.648
Tea1, 5	0.97	1.23	2.55	3.11	12.44	0.274
Tea1, 6	2.63	2.74	12.01	16.10	19.12	0.366
Tea1, 6	3.34	3.59	13.90	14.77	14.17	0.432
Tea1, 6	0.74	2.01	8.76	20.76	21.55	0.312
Tea1, 6	2.31	1.95	11.97	13.91	13.26	0.398
Tea1, 6	0.89	1.84	8.81	15.07	16.15	0.335
Tea1, 11	9.11	6.32	16.00	12.95	6.62	0.661
Tea1, 11	8.34	3.13	11.77	12.42	8.12	0.577
Tea1, 11	7.87	4.94	12.58	12.97	11.39	0.540
Tea1, 11	4.81	3.71	13.11	14.67	9.40	0.504
Tea1, 11	2.98	2.23	10.62	15.96	11.20	0.421
Tea2, 12	0.98	4.10	9.70	14.22	12.43	0.398
Tea2, 12	2.91	6.14	14.87	13.60	16.68	0.436
Tea2, 12	4.20	2.79	12.76	11.89	13.76	0.437
Tea2, 12	1.46	3.96	13.91	11.64	14.67	0.409
Tea2, 12	1.25	2.89	10.73	13.72	15.67	0.367
Tea2, 14	1.53	1.76	4.27	4.91	12.29	0.327
Tea2, 14	1.02	2.74	6.51	8.84	7.62	0.418
Tea2, 14	1.16	3.72	8.85	8.04	9.04	0.439
Tea2, 14	1.99	4.50	8.84	7.72	11.54	0.434
Tea2, 14	0.97	1.80	4.29	5.22	13.02	0.309

Table 13: Fractions weights of different aggregate diameters and values of GMD (Soil samples taken from depth of 10-20 cm, average values of the two sub-samples).

Site	2 mm (g)	1 mm (g)	0.5 mm (g)	0.25 mm (g)	0.053 mm (g)	GMD mm (Geometrical diameter)
Tea1, 1	4.95	3.74	13.78	14.22	15.92	0.439
Tea1, 1	2.26	2.05	9.04	13.87	23.91	0.313
Tea1, 1	4.82	3.96	12.51	13.90	20.85	0.395
Tea1, 1	3.98	4.23	13.02	15.24	16.56	0.421
Tea1, 1	2.53	3.26	11.54	13.69	15.96	0.391
Tea1, 5	3.30	4.03	12.70	10.55	17.94	0.402
Tea1, 5	0.83	1.35	3.90	11.21	15.90	0.288
Tea1, 5	6.48	5.59	14.91	11.81	8.69	0.581
Tea1, 5	1.09	2.29	6.32	10.52	18.49	0.307
Tea1, 5	1.16	1.95	6.22	9.21	12.47	0.345
Tea1, 6	3.22	3.17	13.63	16.70	5.64	0.520
Tea1, 6	0.75	1.91	6.07	7.46	7.35	0.396
Tea1, 6	2.18	1.86	10.40	15.57	19.21	0.343
Tea1, 6	2.30	3.37	15.76	16.17	10.04	0.463
Tea1, 6	2.34	2.55	11.24	13.87	11.99	0.413
Tea1, 11	13.20	6.01	16.40	12.62	9.87	0.657
Tea1, 11	13.11	7.75	15.36	11.32	9.69	0.683
Tea1, 11	15.99	7.84	14.65	10.44	9.54	0.730
Tea1, 11	10.34	4.61	12.16	10.89	5.93	0.686
Tea1, 11	2.70	2.60	8.43	12.97	21.14	0.334
Tea2, 12	0.59	1.62	6.41	8.37	19.23	0.284
Tea2, 12	3.67	3.68	12.93	10.48	18.95	0.396
Tea2, 12	0.84	3.09	9.39	10.86	15.85	0.353
Tea2, 12	3.02	3.45	11.78	12.16	8.93	0.480
Tea2, 12	1.01	1.93	6.97	9.81	15.90	0.321
Tea2, 14	0.58	2.11	4.20	11.57	7.87	0.367
Tea2, 14	0.53	1.78	3.80	5.88	8.15	0.347
Tea2, 14	0.75	2.43	7.00	8.31	11.98	0.356
Tea2, 14	0.60	1.33	5.29	8.58	7.91	0.362
Tea2, 14	0.68	0.29	3.77	5.59	10.41	0.275

Table 14: 13 variables of soil morphology of the 6 sites (5 points in each site).

Sites	BA l	BA m	BA s	PA l	PA m	PA s	Roots	Seeds	Leaves	Stones	Woods	Stems	Inver
Tea1, 1	34	384	507	68	124	186	214	0	0	51	0	8	0
Tea1, 1	0	314	515	34	189	158	143	2	0	42	0	17	1
Tea1, 1	51	325	111	93	200	159	301	0	5	27	0	6	0
Tea1, 1	71	290	148	75	403	321	121	0	0	40	0	0	0
Tea1, 1	30	641	215	71	209	122	133	0	0	20	30	0	3
Tea1, 5	50	464	371	31	82	187	0	0	0	481	0	0	0
Tea1, 5	28	261	315	32	31	50	0	0	0	839	0	0	0
Tea1, 5	0	241	168	30	266	270	0	0	0	464	0	0	0
Tea1, 5	63	362	187	0	35	42	23	0	0	820	0	0	0
Tea1, 5	64	431	256	24	174	130	65	0	0	682	0	5	0
Tea1, 6	86	296	368	34	86	144	130	0	0	9	0	6	0
Tea1, 6	73	401	342	0	80	124	210	0	0	50	4	17	0
Tea1, 6	72	347	358	40	55	131	254	0	0	6	0	2	0
Tea1, 6	124	389	315	19	157	89	78	0	0	68	0	12	2
Tea1, 6	53	375	326	82	168	305	127	0	0	19	0	2	0
Tea1, 11	25	548	318	13	262	167	0	0	5	7	2	9	2
Tea1, 11	8	377	363	34	100	113	52	0	336	39	9	56	0
Tea1, 11	35	234	337	52	102	204	5	0	50	32	1	9	1
Tea1, 11	30	240	390	19	200	168	0	0	15	50	0	15	2
Tea1, 11	19	308	219	23	109	137	0	0	10	49	0	2	0
Tea2, 12	71	700	597	24	133	122	78	3	0	111	0	0	2
Tea2, 12	47	553	490	89	168	80	93	10	0	102	0	0	0
Tea2, 12	52	710	257	62	374	93	73	5	6	108	0	10	1
Tea2, 12	10	666	779	9	111	44	15	5	10	87	5	0	36
Tea2, 12	82	833	414	66	119	57	5	16	0	266	2	22	1
Tea2, 14	20	331	413	81	312	209	47	0	0	548	0	0	1
Tea2, 14	0	336	527	20	271	196	116	4	0	367	0	0	5
Tea2, 14	0	470	445	66	286	207	132	5	0	343	0	0	3
Tea2, 14	88	731	543	10	103	88	80	0	0	133	0	0	4
Tea2, 14	68	399	434	73	320	192	91	10	0	258	0	2	2

Table 15: Aggregates distribution (%) of large, medium size and small biogenic and physical aggregates, each site had 5 points (blank means there was no this kind of aggregate from morphology analysis).

Site	Aggregate distribution mm	BAl %	BAm%	BAs%	PAl%	PAm%	PAs%
Tea1, 1-1	2	4.26	4.33	1.50	4.41	10.43	7.70
	1	10.59	14.89	14.19	14.93	17.89	14.99
	0.5	27.49	22.78	19.27	23.99	23.11	27.66
	0.25	14.77	13.04	11.91	14.31	14.48	14.80
	0.05	8.67	15.22	14.14	16.69	13.92	8.31
Tea1, 1-2	2		13.69	13.20	14.45	11.55	17.11
	1		12.74	13.17	13.57	11.41	10.67
	0.5		18.77	15.34	22.52	21.32	22.98
	0.25		10.54	8.16	14.77	11.64	16.72
	0.05		8.18	12.02	15.42	10.19	6.79
Tea1, 1-3	2	19.03	13.49	13.26	12.88	9.81	12.53
	1	12.16	11.29	13.60	9.51	13.16	13.90
	0.5	16.98	15.35	18.78	18.07	17.43	17.47
	0.25	5.48	8.73	11.69	12.16	11.50	12.47
	0.05	7.51	6.21	5.98	6.73	10.59	18.71
Tea1, 1-4	2	13.38	13.23	10.09	9.05	10.07	16.83
	1	14.42	14.29	11.90	13.40	14.38	11.67
	0.5	24.88	20.45	20.42	21.86	20.52	22.89
	0.25	11.84	9.73	14.05	12.56	10.06	13.30
	0.05	9.03	5.32	8.32	11.27	12.93	5.59
Tea1, 1-5	2	6.76	5.90	5.21	6.14	6.55	9.99
	1	10.45	17.59	9.69	9.31	14.81	10.97
	0.5	23.96	13.89	20.86	23.53	26.49	24.94
	0.25	16.77	15.29	15.64	14.79	14.23	16.22
	0.05	23.88	13.98	17.26	5.57	13.38	6.83
Tae1, 5-1	2	4.74	4.58	6.62	2.38	4.11	3.72
	1	12.67	14.75	12.80	15.38	12.40	14.00
	0.5	21.85	17.41	15.89	22.57	23.10	23.75
	0.25	10.96	7.48	8.54	10.47	11.06	14.47
	0.05	12.81	9.25	12.17	10.47	10.27	13.45
Tae1, 5-2	2	3.82	1.28	1.88	0.65	5.92	5.44

	1	7.01	10.36	9.60	9.80	10.40	12.89
	0.5	14.75	13.66	14.79	17.36	14.38	17.22
	0.25	8.11	8.00	8.62	12.67	10.16	10.94
	0.05	10.56	11.86	5.32	15.28	13.57	13.44
Tae1, 5-3	2		1.55	1.11	1.43	1.51	2.15
	1		7.45	5.19	10.15	9.32	6.51
Site	Aggregate distribution mm	B A l %	B A m %	B A s %	P A l %	P A m %	P A s %
	0.5		15.13	11.85	22.94	12.98	13.52
	0.25		10.02	12.24	14.22	5.60	9.15
	0.05		8.92	8.90	19.68	9.73	19.91
Tae1, 5-4	2	9.91	4.17	2.33		0.87	7.89
	1	7.11	8.79	8.80		12.17	5.13
	0.5	11.79	11.58	12.56		15.68	10.57
	0.25	7.20	8.67	8.79		15.10	10.80
	0.05	4.22	17.96	4.59		20.54	17.38
Tae1, 5-5	2	0.00	3.80	0.00	1.29	7.37	8.57
	1	7.51	11.46	7.11	10.38	9.58	6.79
	0.5	14.83	14.09	14.58	22.11	20.14	14.80
	0.25	10.90	8.36	10.27	14.78	11.01	10.82
	0.05	3.20	10.32	2.53	13.73	8.89	12.42
Tea1, 6-1	2	1.36	2.40	1.73	2.55	0.65	3.78
	1	4.78	5.13	3.86	2.19	3.49	10.23
	0.5	16.63	12.32	10.19	9.59	14.95	28.31
	0.25	13.20	12.18	9.41	12.09	17.09	23.11
	0.05	9.00	22.03	27.21	15.02	16.92	14.83
Tea1, 6-2	2	2.64	5.30	3.29		2.96	5.66
	1	6.85	13.09	9.19		8.14	6.27
	0.5	20.97	17.56	16.88		23.00	16.92
	0.25	14.76	9.85	15.36		15.72	18.06
	0.05	18.57	16.66	26.92		18.34	17.58
Tea1, 6-3	2	4.00	0.00	3.82	7.67	3.33	3.41
	1	10.10	6.04	8.24	11.67	7.97	10.70
	0.5	17.81	14.94	16.37	25.21	19.74	24.91
	0.25	9.00	7.76	12.46	12.02	15.12	16.61
	0.05	16.29	18.08	10.02	8.50	14.53	35.70
Tea1, 6-4	2	2.87	1.74	4.19	3.41	3.44	3.09
	1	5.88	5.94	8.09	5.00	5.29	10.05
	0.5	15.73	8.79	17.65	24.15	13.03	23.11
	0.25	10.19	8.36	13.87	16.30	12.13	20.23
	0.05	8.67	19.24	12.76	18.24	11.28	30.41
Tea1, 6-5	2	2.05	1.91	4.59	1.31	0.59	5.21
	1	4.43	4.48	4.77	4.55	4.79	4.32

	0.5	16.45	15.81	13.74	11.55	11.84	15.05
	0.25	16.83	13.62	11.55	11.16	17.55	19.30
	0.05	23.32	22.78	20.93	19.44	27.43	23.54
Tea1, 11-1	2	19.14	12.81	13.19	3.99	13.07	9.50
	1	8.19	12.06	10.23	13.89	16.76	10.91
	0.5	30.58	20.32	20.76	28.84	20.62	26.67
Site	Aggregate distribution mm	B A l %	B A m %	B A s %	P A l %	P A m %	P A s %
	0.25	11.19	9.15	13.79	16.74	10.10	17.51
	0.05	10.39	12.20	11.75	19.26	8.08	14.63
Tea1, 11-2	2	2.22	4.94	5.53	3.93	7.24	9.67
	1	10.42	10.37	7.96	16.76	12.66	9.87
	0.5	25.28	12.70	16.16	26.05	25.88	20.56
	0.25	22.78	11.39	13.10	14.27	14.63	17.17
	0.05	24.44	13.29	14.91	12.27	15.24	9.21
Tea1, 11-3	2	6.26	6.10	6.66	4.46	4.87	5.96
	1	10.01	11.44	8.78	9.48	10.31	8.50
	0.5	20.55	20.15	17.87	20.85	26.92	20.75
	0.25	15.95	12.76	14.99	15.05	17.12	17.73
	0.05	22.35	7.56	17.17	8.84	12.44	5.61
Tea1, 11-4	2	0.00	10.53	9.09	12.23	7.55	8.93
	1	10.62	11.56	11.46	13.26	11.58	9.76
	0.5	19.65	19.01	15.96	23.13	20.38	23.07
	0.25	12.97	11.52	9.18	12.03	10.93	8.97
	0.05	15.76	9.82	11.74	15.24	7.01	6.04
Tea1, 11-5	2	11.91	4.58	10.51	4.73	7.18	10.65
	1	14.65	11.15	8.52	7.37	16.07	12.03
	0.5	20.85	14.32	19.91	18.61	21.52	24.92
	0.25	9.76	11.36	12.45	15.04	10.89	13.40
	0.05	10.94	16.08	7.61	11.44	12.50	5.08
Tea2, 12-1	2	0.72	0.70	0.71	0.00	0.59	0.29
	1	5.83	4.03	2.82	6.07	6.14	3.14
	0.5	17.01	6.31	4.86	14.26	12.59	7.83
	0.25	8.50	3.57	4.07	11.87	4.47	15.55
	0.05	9.67	11.82	12.72	18.18	8.31	19.67
Tea2, 12-2	2	4.49	2.63	2.99	2.26	5.98	1.15
	1	11.55	9.89	13.27	19.34	12.45	15.50
	0.5	23.71	16.96	19.82	21.14	27.54	24.90
	0.25	13.09	11.60	9.67	12.37	11.42	15.40
	0.05	7.06	15.42	7.34	16.16	7.42	12.34
Tea2, 12-3	2	3.80	3.46	1.40	4.46	2.99	0.69
	1	13.72	10.87	11.72	16.88	15.97	9.14
	0.5	28.56	13.90	20.93	25.19	16.33	26.43

	0.25	13.65	11.69	12.49	11.54	11.61	16.98
	0.05	13.15	17.74	17.46	12.43	14.86	20.77
Tea2, 12-4	2	1.27	3.80	2.53		1.55	3.84
	1	9.87	10.23	5.08		8.34	6.94
	0.5	25.95	12.40	11.26		24.02	20.32
	0.25	18.86	9.24	10.11		14.93	23.38
Site	Aggregate distribution mm	B A l %	B A m %	B A s %	P A l %	P A m %	P A s %
	0.05	31.01	18.25	20.24		11.82	26.12
Tea2, 12-5	2	3.50	1.70	2.96	1.95	1.53	0.00
	1	11.21	4.59	8.91	12.20	8.92	7.18
	0.5	18.33	11.38	10.45	17.73	18.43	23.71
	0.25	12.37	8.07	6.59	12.61	11.13	15.06
	0.05	11.17	13.55	9.11	10.35	7.59	15.55
Tea2, 14-1	2	1.48	7.05	5.85	1.35	1.58	4.50
	1	10.56	8.13	9.71	8.86	9.64	7.87
	0.5	16.30	13.67	13.40	14.22	15.01	16.72
	0.25	11.20	8.62	9.58	10.81	6.92	12.59
	0.05	20.83	9.54	10.16	6.59	10.82	5.29
Tea2, 14-2	2		0.42	0.54	1.91	0.40	0.58
	1		4.71	5.04	4.44	4.39	3.32
	0.5		10.78	9.34	7.53	12.04	7.53
	0.25		7.19	6.39	11.66	8.58	9.65
	0.05		18.76	17.29	19.09	17.76	8.44
Tea2, 14-3	2		2.88	1.09	0.00	1.17	0.52
	1		6.37	5.71	8.49	7.93	5.05
	0.5		8.92	9.84	14.08	13.14	12.75
	0.25		7.80	7.02	9.64	8.23	13.94
	0.05		14.88	12.54	12.72	13.42	9.96
Tea2, 14-4	2	0.78	1.85	2.32	0.00	0.13	2.99
	1	9.19	6.45	5.83	5.37	10.95	13.94
	0.5	16.47	11.66	5.52	20.58	21.16	14.82
	0.25	9.17	6.75	6.45	10.56	11.96	15.38
	0.05	6.75	7.57	14.05	10.29	13.47	16.83
Tea2, 14-5	2	2.73	2.08	2.57	1.77	0.80	0.00
	1	4.34	4.60	4.03	4.19	3.13	2.80
	0.5	11.30	7.82	8.52	11.64	8.05	7.72
	0.25	8.31	8.55	7.16	7.46	10.38	8.64
	0.05	11.66	13.11	12.83	11.49	14.59	13.78

Table 16: GMD (mm) of large, medium size and small biogenic and physical aggregates, each site had 5 points (blank means there was no this kind of aggregate from morphology analysis).

Sites	BA l	BA m	BA s	PA l	PA m	PA s
Tea1, 1	0.617	0.571	0.542	0.556	0.662	0.692
Tea1, 1		0.770	0.714	0.649	0.691	0.765
Tea1, 1	0.900	0.820	0.806	0.747	0.677	0.598
Tea1, 1	0.752	0.844	0.692	0.659	0.666	0.819
Tea1, 1	0.481	0.596	0.506	0.667	0.616	0.697
Tea1, 5	0.592	0.677	0.625	0.624	0.619	0.574
Tea1, 5	0.545	0.523	0.644	0.470	0.559	0.583
Tea1, 5		0.532	0.471	0.461	0.557	0.402
Tea1, 5	0.803	0.461	0.652		0.439	0.469
Tea1, 5	0.608	0.599	0.623	0.510	0.649	0.571
Tea1, 6	0.490	0.370	0.311	0.375	0.379	0.520
Tea1, 6	0.447	0.549	0.403		0.468	0.463
Tea1, 6	0.514	0.392	0.554	0.678	0.494	0.396
Tea1, 6	0.540	0.371	0.521	0.451	0.485	0.406
Tea1, 6	0.371	0.371	0.406	0.364	0.322	0.394
Tea1, 11	0.748	0.694	0.663	0.526	0.798	0.590
Tea1, 11	0.437	0.539	0.509	0.617	0.584	0.639
Tea1, 11	0.476	0.662	0.507	0.592	0.566	0.634
Tea1, 11	0.473	0.686	0.647	0.642	0.705	0.743
Tea1, 11	0.721	0.514	0.691	0.535	0.651	0.763
Tea2, 12	0.501	0.378	0.330	0.386	0.521	0.316
Tea2, 12	0.654	0.494	0.663	0.574	0.689	0.571
Tea2, 12	0.589	0.479	0.489	0.632	0.559	0.446
Tea2, 12	0.398	0.471	0.378		0.520	0.403
Tea2, 12	0.570	0.421	0.573	0.568	0.578	0.455
Tea2, 14	0.437	0.621	0.603	0.580	0.544	0.639
Tea2, 14		0.353	0.360	0.350	0.364	0.414
Tea2, 14		0.435	0.430	0.466	0.467	0.447
Tea2, 14	0.589	0.549	0.407	0.486	0.509	0.505
Tea2, 14	0.457	0.409	0.420	0.445	0.353	0.337